

# Dense Cores in Dark Clouds. XIV. $\text{N}_2\text{H}^+(1-0)$ maps of dense cloud cores

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## ABSTRACT

We present results of an extensive mapping survey of  $\text{N}_2\text{H}^+(1-0)$  in about 60 low mass cloud cores already mapped in the  $\text{NH}_3(1,1)$  inversion transition line. The survey has been carried out at the FCRAO antenna with an angular resolution of  $54''$ , about 1.5 times finer than the previous ammonia observations made at the Haystack telescope. The comparison between  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  maps shows strong similarities in the size and morphology of the two molecular species indicating that they are tracing the same material, especially in starless cores. Cores with stars typically have map sizes about a factor of two smaller for  $\text{N}_2\text{H}^+$  than for  $\text{NH}_3$ , indicating the presence of denser and more centrally concentrated gas compared to starless cores. The mean aspect ratio is  $\sim 2$ . Significant correlations are found between  $\text{NH}_3$  and  $\text{N}_2\text{H}^+$  column densities and excitation temperatures in starless cores, but not in cores with stars, suggesting a different chemical evolution of the two species. Starless cores are less massive ( $< M_{\text{vir}} > \simeq 3 M_{\odot}$ ) than cores with stars ( $< M_{\text{vir}} > \simeq 9 M_{\odot}$ ). Velocity gradients range between 0.5 and 6 km/s/pc, similar to what has been found with  $\text{NH}_3$  data, and the ratio  $\beta$  of rotational kinetic energy to gravitational energy have magnitudes between  $\sim 10^{-4}$  and 0.07, indicating that rotation is not energetically dominant in the support of the cores. “Local” velocity gradients show significant variation in both magnitude and direction, suggesting the presence of complex motions

not interpretable as simple solid body rotation. Integrated intensity profiles of starless cores present a “central flattening” and are consistent with a spherically symmetric density law  $n \propto r^{-\alpha}$  where  $\alpha = 1.2$  for  $r < r_{\text{break}}$  and  $\alpha = 2$  for  $r > r_{\text{break}}$ , where  $r_{\text{break}} \sim 0.03$  pc. Cores with stars are better modelled with single density power laws with  $\alpha \geq 2$ , in agreement with observations of submillimeter continuum emission. Line widths change across the core but we did not find a general trend: there are cores with significant positive as well as negative linear correlations between  $\Delta v$  and the impact parameter  $b$ . The deviation in line width correlates with the mean line width, suggesting that the line of sight contains  $\sim 10$  coherence lengths. The corresponding value of the coherence length,  $\sim 0.01$  pc, is similar to the expected cutoff wavelength for MHD waves. This similarity may account for the increased “coherence” of line widths on small scales. Despite of the finer angular resolution, the majority of  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  maps show a similar “simple” structure, with single peaks and no elongation.

*Subject headings:* molecular data – ISM: clouds, molecules, structure – radio lines: ISM

## 1. Introduction

Dense cores in dark clouds have been extensively studied through observations of the inversion transition lines of ammonia (Myers & Benson 1983; Benson & Myers 1989, hereafter BM89) and other high density tracers, including CS (Zhou et al. 1989),  $\text{C}_2\text{S}$  (Suzuki et al. 1992) and  $\text{HC}_3\text{N}$  (Fuller & Myers 1993). Molecular emission maps have improved our understanding of cloud structure and have given us insights on the initial conditions of the star forming process. It is now well established that low mass cores as mapped in  $\text{NH}_3$  lines are about 0.1 pc in size, have kinetic temperatures of about 10 K, and gas number density of  $\sim 3 \times 10^4 \text{ cm}^{-3}$  (BM89). Generally, cores have elongated maps with typical aspect ratio of 2 (Myers et al. 1991; Ryden 1996). Goodman et al. (1993) used ammonia maps to measure velocity gradients; they found typical magnitudes between 0.3 and  $4 \text{ km s}^{-1} \text{ pc}^{-1}$  and conclude that rotation is not energetically dominant in the support of cores.

The upgrade of the 37-m Haystack telescope <sup>1</sup> at 3 mm (Barvainis & Salah 1994)

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<sup>1</sup>Radio Astronomy observations at the Haystack Observatory of the Northeast Radio Observatory

enabled high spatial (and spectral) resolution observations of the molecular ion  $\text{N}_2\text{H}^+$  towards those cores already studied in  $\text{NH}_3$  (Benson, Caselli & Myers 1998, hereafter BCM98). The  $J = 1 \rightarrow 0$  rotational transition of diazenylium has been detected in most (94%) of the cores indicating that this species is widespread and easy to detect. Moreover, a good correlation between  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  velocities and line widths indicates that the two species are probably tracing the same material.  $\text{N}_2\text{H}^+$  is known to be a selective tracer of quiescent gas (Turner & Thaddeus 1977; Womack et al. 1992; Bachiller 1996) and is particularly suitable for studying the structure and kinematics of cold star forming cores. Being an ion, diazenylium is also important to trace the ionized gas and to give information about the coupling between ions and neutrals in star-forming dense cores (BCM98). We point out that  $\text{N}_2\text{H}^+$ , formed through the ion-molecule reaction  $\text{N}_2 + \text{H}_3^+$  and mainly destroyed by CO and electrons, traces molecular nitrogen,  $\text{N}_2$ , which is a major repository of nitrogen.  $\text{N}_2\text{H}^+$  is thought to be a “late depleter” (Bergin & Langer 1997; Aikawa et al. 2001; Caselli et al. 2001b) and so is a good tracer of dense core gas.

In this paper we present  $\text{N}_2\text{H}^+$  maps of 57 low mass cloud cores made at the FCRAO 14-m antenna equipped with the QUARRY receiver (Erickson et al. 1992). The list of objects is the same as in BCM98 and it includes all cores already mapped in  $\text{NH}_3(1,1)$ . The angular resolution of the present observations ( $54''$ ) is 1.5 times finer than the previous  $\text{NH}_3$  study, allowing a more detailed analysis of the morphology and internal motions of dense cores. Technical details of the observations made at FCRAO are reported in Sect. 2. Results and discussion of this mapping program, including integrated intensity maps, column density, size, and mass estimates, velocity gradients, intensity profiles, and the variation of line widths across the cores, are shown in Sect. 3. The main conclusions of this work are summarized in Sect. 5.

## 2. FCRAO Observations

The  $J = 1 \rightarrow 0$   $\text{N}_2\text{H}^+$  observations were made in March and June 1995 and in March 1996 at the FCRAO 14 m telescope at New Salem, Massachusetts. We used the 15 element QUARRY receiver (Erickson et al. 1992) and the autocorrelation spectrometer with a bandwidth of 20 MHz over 1024 channels, giving a spectral resolution of  $\sim 20$  kHz or  $0.063$  km s $^{-1}$ . The beam efficiency ( $\eta_B$ ) was 0.51 at 93 GHz (Pratap et al. 1997) and the main beam width at half power (HPBW) was  $54''$ . The typical system temperature at 93 GHz was  $\sim 500$  K. The data were acquired in frequency-switching mode with a throw of 8 MHz

and calibrated using the ambient load vane method. The rms pointing error, estimated by observing Venus and Mars, was  $\sim 5''$ .

### 3. Results and discussion

#### 3.1. Integrated intensity maps

We have completed 13 Nyquist sampled maps ( $25''$  spacing) and 34 beam sampled maps ( $50''$  spacing) to intensity levels below half maximum. An additional 10 beam-sampled maps are not complete below the half maximum contour. Table 1 reports in columns 2 and 3 the coordinates of the (0,0) map position. These do not always correspond to the coordinates quoted in BM89 because of recentering of the map to include all the emitting region. The peak position is reported in columns 4 and 5 as offsets from the (0,0) coordinates. In column 6, the one-sigma level of the noise in the off-line channels (in antenna temperature units) is listed. The integrated intensity of the emission at the map peak is in column 7; the error on the integrated intensity is  $\sigma_I = \Delta T_A^* \times \sqrt{N_{\text{ch}}} \times \Delta v_{\text{res}}$ , where  $N_{\text{ch}}$  is the number of channels in the integrated intensity (listed in column 8), and  $\Delta v_{\text{res}}$  ( $= 0.063 \text{ km s}^{-1}$ ) is the velocity resolution. Column 9 of Tab. 1 indicates the map grid spacing: beam sampled maps ( $50''$  spacing) are indicated with a “B”, whereas Nyquist sampling ( $25''$  spacing) is marked by an “N”. The size of the mapped area is given in column 10. The association with an IRAS source is indicated in column 11.

A sample of the  $\text{N}_2\text{H}^+(1-0)$  data is shown in Fig. 1, where the averaged spectrum, i.e. the sum of all the spectra inside the half maximum map contour, is presented for three starless cores (L1498, L1544, TMC-2) and three cores with stars (L1489, L1228, L1251E). The line profiles dramatically change from quiescent starless cores, such as L1498, to L1251E, the core with the most complex velocity structure (see Sect. 3.6). Integrated intensity maps are shown in Figure 2. All the maps have the same angular scale and the contours are between 20% and 95% of the peak, in steps of  $0.15 \times$  the peak intensity. The mapped area is shown in the figure (the map type is reported in Tab. 1). IRAS sources associated with cores are marked with stars. The criteria of association are described in Jijina, Myers & Adams (1999).

#### 3.2. Column density

The  $\text{N}_2\text{H}^+(1-0)$  line presents hyperfine structure (e.g. Caselli, Myers & Thaddeus 1995; BCM98) and the hfs fitting program in CLASS (Forveille, Guilloteau & Lucas 1989),

with the hyperfine frequencies adopted from Caselli et al. 1995, has been used to determine LSR velocities ( $V_{\text{LSR}}$ ), intrinsic line widths ( $\Delta v$ ), total optical depths ( $\tau_{\text{TOT}}$ ), and excitation temperatures ( $T_{\text{ex}}$ ). These parameters are listed in Table 2 for the peak spectrum and the spectrum averaged inside the half maximum contour. Column 6 of Tab. 2 reports the  $\text{N}_2\text{H}^+$  column density ( $N_{\text{tot}}$ ), which has been calculated following the procedure described in Caselli et al. 2001b<sup>2</sup>. In the case of optically thin emission,  $T_{\text{ex}} = 5$  K has been assumed to compute  $N_{\text{tot}}$ . It is interesting to note that the peak column density averaged over the whole sample is  $(7 \pm 5) \times 10^{12} \text{ cm}^{-2}$ , about three times smaller than the averaged column density in BCM98 (when the same method is applied). This discrepancy is probably due to the smaller beam of BCM98 observations (factor of 2) and suggests the presence of density structure in the studied cores (see Sect. 3.5).

BCM98 found good correlations between  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  velocities and line widths, but no correlation between column densities of the two species. The authors claimed that this result may be due to the different spatial resolutions in the  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  studies, and to the fact that  $\text{N}_2\text{H}^+$  emission may have a different peak position. In this paper, the peak of the  $\text{N}_2\text{H}^+$  emission has been determined and we can then compare the peak column densities reported in Tab. 1 with those of  $\text{NH}_3$ . The result is shown in Fig. 3a, where only cores with  $N/\sigma_N > 2$  have been included. Indeed, the entire sample does not show a significant correlation between  $N(\text{N}_2\text{H}^+)$  and  $N(\text{NH}_3)$ . The scatter may be due to the significant errors associated with  $\text{N}_2\text{H}^+$  column densities, caused by the large uncertainties on the total optical depth probably related to the presence of excitation anomalies (e.g. Caselli et al. 1995). However, it is interesting to note that for starless cores the correlation between  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  column densities is significant (best-fit line in Fig. 3a):

$$N_{\text{starless}}(\text{N}_2\text{H}^+) \times 10^{12} = (2 \pm 2) + (0.6 \pm 0.3) N_{\text{starless}}(\text{NH}_3) \times 10^{14} \text{ cm}^{-2}, \quad (1)$$

where the quantities following  $\pm$  are 1-sigma uncertainties and where the linear correlation coefficient is  $cc = 0.52$ . The presence of a young stellar object probably affects the chemistry in a way that differentiation between the two species starts to be evident. Fig. 3a shows that in “ $\text{NH}_3$ -rich starred” cores, the  $N(\text{N}_2\text{H}^+)/N(\text{NH}_3)$  column density ratio is smaller than in the rest of the sample. This may indicate that the  $\text{N}_2\text{H}^+(1-0)$  line is more optically thick and probably more affected by the lower density foreground material, so that a correct measurement of  $\tau$  is difficult to obtain without a correct radiative transfer calculation.

The  $\text{N}_2\text{H}^+$  integrated intensity is plotted versus the “equivalent”  $\text{NH}_3$  integrated

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<sup>2</sup>The approximated method used by BCM98, which assumes  $J_\nu(T_{\text{ex}}) = T_{\text{ex}}$ , with  $J_\nu(T)$  the equivalent Rayleigh–Jeans temperature, underestimates the  $\text{N}_2\text{H}^+$  column density by a factor of about four compared to the present calculation.

intensity ( $T_A \times \Delta v$ ) in Fig. 3b. Although the associated uncertainties are significantly smaller than in the case of column density (see Tab. 1), the dispersion is still large. As in the previous case, starless cores show a more significant correlation:

$$I_{\text{starless}}(\text{N}_2\text{H}^+) = (0.4 \pm 0.3) + (2.0 \pm 0.7)(T_A \times \Delta v)_{\text{starless, NH}_3} \text{ K km s}^{-1}, \quad cc = 0.67. \quad (2)$$

In Fig. 3c,  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  excitation temperatures are plotted. Once again, the correlation is strong for starless cores:

$$T_{\text{ex, starless}}(\text{N}_2\text{H}^+) = (1.4 \pm 0.8) + (0.4 \pm 0.1)T_{\text{ex, starless}}(\text{NH}_3), \quad (3)$$

with  $cc = 0.79$  (dotted line in Fig. 3c), whereas no significant correlation is present in cores with stars. Typically,  $T_{\text{ex}}(\text{NH}_3) > T_{\text{ex}}(\text{N}_2\text{H}^+)$ , which suggests that the critical density  $n_{\text{cr}}(\text{NH}_3) < n_{\text{cr}}(\text{N}_2\text{H}^+)$ . In fact,  $n_{\text{cr}}(\text{N}_2\text{H}^+) = 2 \times 10^5 \text{ cm}^{-3}$  (Ungerechts et al. 1997), about one order of magnitude larger than that of  $\text{NH}_3$  ( $2 \times 10^4 \text{ cm}^{-3}$ ; Swade 1989).

Correlations between velocities and linewidths of the  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  peak spectra are identical to those found in BCM98 and we will not further discuss them. This paper will concentrate on the structure and internal motions of individual cores.

### 3.3. Sizes and masses

Sizes of the mapped cores are listed in Tab. 3. The 2D gaussian fitting routine in GRAPHIC (Buisson et al. 2001) has been used to find the position angle, the major and minor axis (see columns 2, 3, and 4, respectively). The reported source sizes have been corrected for beam size, i.e. we subtracted the gaussian beam size in quadrature for each dimension. Aspect ratios (column 5) range between 1.1 and 6.4 with mean  $\pm$  standard deviation  $2.0 \pm 0.9$ . The size  $r$  in column 6 and 7 is the half power radius, given by the geometric mean of the semimajor and semiminor axis. Note that  $r = R/2$ , where  $R$  is the size listed in Table 5 of BM89. The cloud distance is reported in column 8. Comparing the size of  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  cores with associated stars we find a good correlation ( $cc = 0.8$ ):

$$r_{\text{star}}(\text{NH}_3) = (-0.02 \pm 0.03) + (2.2 \pm 0.4)r_{\text{star}}(\text{N}_2\text{H}^+) \text{ pc}, \quad (4)$$

which indicates that the emission of the two molecules have similar morphology, despite the different beam sizes. The factor of 2 difference is probably due to differences in the critical density  $n_{\text{cr}}$  of the two tracers since map sizes are already corrected for beam smoothing and the resolution ratio is 1.5, less than the typical ratio of radii, 1.8. Indeed, it is interesting to note that the above relation pertains to cores with stars, given that for starless cores we find:

$$r_{\text{starless}}(\text{NH}_3) = (-0.01 \pm 0.01) + (0.9 \pm 0.3)r_{\text{starless}}(\text{N}_2\text{H}^+) \text{ pc} \quad (cc = 0.7) \quad (5)$$

These relations suggest that  $\text{N}_2\text{H}^+(1-0)$  is tracing higher density material than  $\text{NH}_3(1,1)$ , and that cores with stars are denser and more centrally condensed than starless cores. On the other hand, in starless cores, the two lines originate from the same regions. Figure 4 shows the distribution of  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  core radii in (i) the entire sample, (ii) cores with stars, and (iii) starless cores; the two tracers span different size ranges only for cores with stars. On average, starless cores have smaller sizes than cores with stars. For 35 cores with stars, the  $\text{N}_2\text{H}^+$  map radius  $r$  has mean  $\pm$  standard error of the mean (s.e.m.)  $0.069 \pm 0.005$  pc, while for 19 starless cores,  $\langle r \rangle_{\text{starless}} = 0.054 \pm 0.005$  pc.

The virial mass of an equivalent uniform density sphere:

$$M_{\text{vir}}(M_{\odot}) = 210 \times r(\text{pc}) \times \Delta v_{\text{m}}^2 (\text{km}^2 \text{s}^{-2}), \quad (6)$$

is listed in column 3 of Tab. 4. The corresponding number density  $n_{\text{vir}}$  is in column 2.  $\Delta v_{\text{m}}$  in eqn. 6 is the FWHM of the molecule of mean mass (2.33 amu, assuming gas with 90% of  $\text{H}_2$  and 10% He):

$$\Delta v_{\text{m}}^2 = \Delta v^2 + 8 \ln 2 \frac{kT}{m_{\text{H}}} \times \left( \frac{1}{2.33} - \frac{1}{m_{\text{N}_2\text{H}^+}} \right), \quad (7)$$

where  $\Delta v$  is the intrinsic linewidth of the  $\text{N}_2\text{H}^+$  peak spectrum (see Tab. 2), and  $m_{\text{N}_2\text{H}^+}$  ( $= 29$  amu) is the mass of the  $\text{N}_2\text{H}^+$  molecule. Column 4 reports the  $\text{N}_2\text{H}^+$  fractional abundance:  $X(\text{N}_2\text{H}^+) = N(\text{N}_2\text{H}^+)/N(\text{H}_2)$ , where  $N(\text{H}_2) = (4/3) \times (n_{\text{vir}}/1.11) \times r$ , and the factor 1.11 takes into account the difference between  $n_{\text{vir}}$ , the “virial” number density of the molecule of mean mass, and  $n_{\text{vir}}(\text{H}_2)$ . The  $\text{N}_2\text{H}^+$  column density used for estimating  $X(\text{N}_2\text{H}^+)$  is the peak or the average column density, depending on the associated errors. The average value is  $\langle X(\text{N}_2\text{H}^+) \rangle = (3 \pm 1) \times 10^{-10}$ , close to that found in BCM98.

Tab. 4 also gives in column 5 the volume density  $n_{\text{ex}}$ , calculated from the  $(n_{\text{ex}}/n'_{\text{cr}})$  ratio (see eqn. 8 below), where  $n'_{\text{cr}}$  is the critical density (corrected for trapping) of the  $\text{N}_2\text{H}^+(1-0)$  line; and in column 6 the “excitation” mass of a uniform core ( $M_{\text{ex}} = (4/3) \pi m n_{\text{ex}} r^3$ ). The quantity  $n_{\text{ex}}/n'_{\text{cr}}$  has been obtained by using the expression for two-level statistical equilibrium (Genzel 1992):

$$\frac{n_{\text{ex}}}{n'_{\text{cr}}} = \frac{\tilde{T}_{\text{ex}} - \tilde{T}_{\text{cb}}}{\frac{h\nu}{k} \left( 1 - \frac{\tilde{T}_{\text{ex}}}{\tilde{T}_{\text{kin}}} \right)} \quad (8)$$

where  $\nu$  is the transition frequency,  $h$  and  $k$  are the constants of Planck and Boltzmann, respectively,

$$n'_{\text{cr}} = n_{\text{cr}} \times \frac{1 - \exp(-\tau)}{\tau}, \quad (9)$$

and

$$\tilde{T} = \left( \frac{h\nu}{k} \right) \left( 1 - \exp \left( -\frac{h\nu}{kT} \right) \right)^{-1}. \quad (10)$$

In eqn. 9,  $\tau$  is the optical depth of a “typical” hyperfine component ( $\sim \tau_{\text{TOT}}/9$ ).  $T_{\text{ex}}$ ,  $T_{\text{cb}}$ , and  $T_{\text{kin}}$  in eqn. 8 are the excitation, the cosmic background, and the kinetic temperatures, respectively. We assumed  $T_{\text{cb}} = 2.7$  K,  $T_{\text{kin}} = 10$  K (see BM89), whereas  $T_{\text{ex}}$  is the excitation temperature of the averaged spectrum (see Tab. 2). The error on  $n_{\text{ex}}$  is obtained by propagating the error associated with  $T_{\text{ex}}$  and  $\tau$  into eqn. 8 (see Appendix A).

In Fig. 5  $M_{\text{ex}}$  is plotted as a function of  $M_{\text{vir}}$  for the whole sample (with the exception of cores with (i)  $M_{\text{ex}}/\sigma_{M_{\text{ex}}}$  or  $M_{\text{vir}}/\sigma_{M_{\text{vir}}} < 2$ , (ii) assumed excitation temperature, and (iii) deconvolved size less than the beam size, as in the case of B335). In average, starless cores are less massive than cores with stars:  $\langle M_{\text{vir}} \rangle_{\text{star}} = 9 \pm 3 M_{\odot}$ ,  $\langle M_{\text{vir}} \rangle_{\text{starless}} = 3.3 \pm 0.4 M_{\odot}$ . However, there is not significant difference in the  $M_{\text{ex}}/M_{\text{vir}}$  ratio between the two classes of cores (in average  $\langle M_{\text{ex}}/M_{\text{vir}} \rangle_{\text{star}} = 1.4 \pm 0.3$ , and  $\langle M_{\text{ex}}/M_{\text{vir}} \rangle_{\text{starless}} = 1.3 \pm 0.3$ ). We note that the assumption of a uniform density sphere to estimate the virial mass is a very crude one. In Sect. 3.5 we will show that spheroidal cores are consistent with density profiles of the form  $n(r) \propto r^{-\alpha}$ , with  $\langle \alpha \rangle \sim 2$ , although most of the starless cores present “central flattening”, at impact parameters  $b \leq 5000$  AU. If cores were approximated with singular isothermal spheres, our virial mass estimates should be reduced by a factor of 1.6.

### 3.4. Velocity Gradients

Following Goodman et al. (1993) (hereafter GBF93), a least squares fitting of a velocity gradient has been performed in all the cores with at least 9 positions with a good determination of the LSR velocity  $V_{\text{LSR}}$ . In Table 5, the magnitude of the velocity gradient  $\mathcal{G}$  and its direction ( $\theta_{\mathcal{G}}$ , the direction of increasing velocity, measured east of north) are reported in column 3 and 4, respectively; the number of velocity points used in the fit is in column 2; the product between  $\mathcal{G}$  and the core size  $r$ , or the typical velocity shift across the map, is in column 5; the ratio  $\beta$  of rotational kinetic energy to gravitational energy (see eqn. (6) in GBF93) is shown in column 6.

For thirteen of the cores in Tab. 5, the same quantities have been calculated by GBF93 using  $\text{NH}_3$  maps (see their Table 2). By comparing the magnitude of the velocity gradient calculated from  $\text{N}_2\text{H}^+(1-0)$  and  $\text{NH}_3(1,1)$  data ( $\mathcal{G}_{\text{N}_2\text{H}^+}$  and  $\mathcal{G}_{\text{NH}_3}$ , respectively) we found no correlation and the majority of the cores (with the exception of L1495 and L1251E)

have  $\mathcal{G}_{\text{N}_2\text{H}^+} > \mathcal{G}_{\text{NH}_3}$ , although the scatter is large (the average of the  $\mathcal{G}_{\text{N}_2\text{H}^+}/\mathcal{G}_{\text{NH}_3}$  ratio  $\pm$  standard deviation is  $1.6 \pm 1.0$ ). On the other hand, the correlation between  $\Theta_{\mathcal{G}}(\text{N}_2\text{H}^+)$  and  $\Theta_{\mathcal{G}}(\text{NH}_3)$  is significant ( $cc = 0.7$ ). The slightly larger magnitude of the velocity gradient in most of  $\text{N}_2\text{H}^+$  cores probably reflects the finer spatial resolution of these observations compared to that for  $\text{NH}_3$ . In fact, a larger beam will tend to smooth out  $V_{\text{LSR}}$  variations across the map. We note, however, that this also implies broader  $\text{NH}_3$  lines, which are not observed (see end of Sect. 3.2 and BCM98). Finally,  $\beta$  is similar in  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  cores: in those cores which are in common in the two samples, the average value of  $\beta$  is  $\sim 0.02$  from  $\text{N}_2\text{H}^+$  data, and  $\sim 0.03$  from  $\text{NH}_3$  data.

Tab. 5 also lists the average value and its standard deviation (columns 7 and 8, respectively) of the fit residuals  $V_{\text{LSR}}(i) - V_{\text{fit}}(i)$  across the core, where  $V_{\text{fit}}(i)$  is the LSR velocity at position  $(\alpha(i), \beta(i))$  determined by the least square fit of a linear velocity gradient. These quantities are useful to describe the more complex motions in the core and will be discussed in section 3.6.

For 12 cores it has also been possible to determine the magnitude and the direction of “local” velocity gradients, i.e. variations of  $V_{\text{LSR}}$  in portions of a cloud core. The selected cores have at least 12 observed positions where the determination of  $V_{\text{LSR}}$  is possible via hfs fitting (see Sect. 3.2). In each of these cores, the least square fitting routine to determine  $\mathcal{G}$  and  $\Theta_{\mathcal{G}}$  has been successively applied to adjacent grids of  $3 \times 3$  points spaced by  $\leq 35''$  or  $\leq 71''$  (depending on the map type; see Tab. 1, column 8). Incomplete grids of at least 7 points have also been included in the computation of “local” velocity gradients. The results are shown in Fig. 6, for the 12 selected cores, together with the “global” velocity gradient. The arrows point toward increasing  $V_{\text{LSR}}$ . From the figure it is evident that many cores present internal variations of the magnitude and direction of the velocity gradient (see, in particular, L1228 and L1251E), which illustrates the presence of complex motions not interpretable as simple solid body rotation of the whole core.

The velocity gradient maps of Fig. 6 show a wide range of structure which departs from the uniform rotation model used by GBF93 to analyse the velocities of the corresponding  $\text{NH}_3$  maps which generally had fewer data points than do the present  $\text{N}_2\text{H}^+$  maps. Of the 9 maps in Fig. 6 having at least 5 velocity gradient vectors, only 2 – L1512 and L1221 – have velocity gradient maps which are nearly uniform in both magnitude and direction, indicating simple uniform rotation. The rest show patterns which are fairly uniform in magnitude but not direction (L183, L1544), uniform in direction but not magnitude (L483), or which have significant variation in both magnitude and direction (L1228, L1251E, L43, and L1498). The most complex pattern is in L1251E, which shows distinct reversal of gradient direction between the East and West parts of the core. The departures from

uniform rotation are most pronounced in the cores having associated YSOs and outflows (L483, L43, L1228, and L1251E). But substantial departures are also evident in the starless cores L183, L1544, and L1498 – which show evidence of contracting motion in CS(2–1) (Tafalla et al. 1998; Lee, Myers & Tafalla 1999, 2000), although HCO<sup>+</sup>(3–2) lines show no infall asymmetry toward L1498 (Gegersen & Evans 2000). These results are consistent with a picture where simple uniform core rotation is rare, where more turbulent motions are relatively common, and where such turbulence is associated with cores with YSOs and outflows or with starless cores having evidence of inward flows. An interpretation of dense core velocity gradients in terms of turbulent motions was recently presented by Burkert & Bodenheimer (2000).

We note that cores with complex velocity gradient maps should be poorly fit by a simple model of uniform rotation, and inspection of the “normalized” standard deviation of the fit residuals  $s_{<V_{\text{LSR}}-V_{\text{fit}}>} / (\mathcal{G} \times r)$ , as well as  $s_{<V_{\text{LSR}}-V_{\text{fit}}>}$  (see Tab. 5), bears out this expectation. The most uniform pattern of gradient vectors, for L1512 (Fig. 6), corresponds to one of the smallest “normalized” fit residuals, 0.3, while the most complex pattern, for L1251E, has one of the largest  $s_{<V_{\text{LSR}}-V_{\text{fit}}>} / (\mathcal{G} \times r)$ , 2.4 (and the largest  $s_{<V_{\text{LSR}}-V_{\text{fit}}>}$ , 0.36 km s<sup>−1</sup>). The “normalized” standard deviation relative to L1498 lies between L1512 and L1544. This suggests that L1498 is probably in an evolutionary stage later than the “static” core L1512 and earlier than the collapsing L1544. In fact, L1498 has been described as an extremely quiescent core (Lemme et al. 1995, Wolkovitch et al. 1997) with evidence of slow contraction, outer envelope growth and strong chemical differentiations (Kuiper, Langer & Velusamy 1996; Tafalla et al. 2001). Large values of  $s_{<V_{\text{LSR}}-V_{\text{fit}}>} / \mathcal{G} \times r$  ( $\sim 1$ ) are also present in TMC–2, an infall candidate with CS asymmetry (Lee, Myers & Tafalla 2000).

### 3.5. Integrated intensity profiles

The “standard model” of isolated star formation (Shu, Adams, & Lizano 1987) states that cores lose magnetic support by ambipolar diffusion until they become so concentrated that the central regions are gravitationally unstable and start to collapse. The collapse of the central region deprives the above layers of pressure support and causes them to also fall towards the center. In this way, gravitational collapse propagates from the inside out and continues until the core runs out of mass or a powerful wind from the central star-disk system reverses the collapse and disperses the core.

Some critical parameters of the “standard model” are unconstrained. The two most crucial unknowns are the radial dependence of density and turbulent velocity (alternatively of magnetic field), which together determine how gravitational collapse occurs. For example,

a change in the density power law from  $r^{-2}$  (isothermal sphere, Shu 1977) to  $r^{-1}$  (logotropic sphere, McLaughlin & Pudritz 1996), changes completely the core star forming properties (McLaughlin & Pudritz 1997), and our observations are not fine enough at this point to rule out any of these options. In fact, our ignorance of these basic core properties constitutes the most serious limitation in our understanding of how stars form in isolated dense cores.

From submillimeter continuum dust emission, Ward–Thompson et al. 1994 found that the radial density profiles of pre–stellar cores are significantly different from the singular isothermal sphere, and qualitatively consistent with models of magnetically–supported cores undergoing ambipolar diffusion (e.g. Ciolek & Mouschovias 1995). Typically, the radial density profile inferred assuming a constant dust temperature is as flat as  $\rho(r) \propto r^{-\alpha}$ , with  $\alpha \sim 0.4\text{--}1.2$ , depending on the core shape, at radii less than  $\sim 4000$  AU, and approaches  $\rho(r) \propto r^{-2}$  only between  $\sim 4000$  AU and  $\sim 15000$  AU (André, Ward–Thompson & Motte 1996; Ward–Thompson, Motte, & André 1999; Alves et al. 2001). However, recent model calculations of the dust temperature in pre–stellar cores (Zucconi et al. 2001; Evans et al. 2001) predict a temperature gradient, with a drop from  $\sim 14$  K at the edges to  $\sim 7$  K at the centers, which implies more peaked density distributions than in the isothermal case. On the other hand, millimeter continuum observations of circumstellar envelopes of low–mass protostars are in good agreement with the standard protostellar model of Shu et al. (1987), with power–law density gradients such as  $\rho(r) \propto r^{-2}$  or  $r^{-1.5}$  (Motte & André 2000).

$\text{N}_2\text{H}^+(1\text{--}0)$  maps can be used to investigate the column density structure of dense cores and make comparisons with results from submillimeter maps. We already noted (see Sect. 3.2) that the uncertainty associated with  $\text{N}_2\text{H}^+$  column density is quite large, especially for low sensitivity spectra (such as those away from the map peak), because of the difficulty in determining an accurate value of the total optical depth of the  $\text{J}=1\text{--}0$  transition. Therefore, instead of using  $\text{N}_2\text{H}^+$  column density profiles, we made plots of the  $\text{N}_2\text{H}^+(1\text{--}0)$  intensity integrated below the seven hyperfine components as a function of impact parameter. The use of integrated intensity may be dangerous in those cases where the optical depth is large (when the column density is no longer simply proportional to the integrated intensity), but we will see that our conclusions are not affected by this problem.

The integrated intensity profiles of spheroidal cores (with aspect ratio  $\leq 2$ , see Tab. 3) have been fitted using two models. Model 1 consists of a spherically symmetric cloud model with a density profile  $\rho(r) \propto r^{-\alpha}$ . The resultant intensity profile vs. impact parameter  $b$  ( $I \propto b^{-p}$ , with  $p = \alpha - 1$ ), has been convolved with a 2D Gaussian, with FWHM equal to the FCRAO beam ( $54''$ ). For each core, we change the value of  $p$  from 0.5 to 2.0, in steps of 0.1, and find the best  $\chi^2$  convolved profile and the corresponding  $\alpha$  value. Fig. 7 (thin curves) and Tab. 6 (columns 2 and 3) show the results of this procedure.

Model 2 considers a spherically symmetric cloud with a radial density profile inferred from submillimeter continuum observations of spheroidal cores, with  $\rho(r) \propto r^{-1.2}$  at  $r < r_{\text{break}}$ , and  $\rho(r) \propto r^{-2}$  at  $r > r_{\text{break}}$  (see e.g. André, Ward–Thompson & Barsony 2000). The two profiles have been convolved with the FCRAO beam and joined at  $r_{\text{break}}$ . We run several models with different values of impact parameter at the break ( $b_{\text{break}}$  from  $10''$  to  $100''$ , in steps of  $5''$ ). From the  $\chi^2$  minimization, we determined  $b_{\text{break}}$  for each core (see column 4 of Tab. 6). Model 2 profiles are shown in Fig. 7 by the dashed curves.

The comparison between the  $\chi^2$  values of Model 1 and 2 (columns 3 and 5 of Tab. 6) allows one to find the appropriate model density profile for each object. It is interesting to note that most (6 out of 9) of the cores with stars are best fitted with single power laws. With the exception of Per 6, L1495, and L43, all cores with stars have  $b_{\text{break}} = 10''$  (the minimum value in Model 2), which is equivalent to having a single slope. Starless cores show a different behaviour: 6 out of 8 objects have intensity profiles consistent with central flattening at impact parameters less than  $\sim 5000$  AU. This is in good agreement with results from submillimeter continuum observations. These results are interpreted by Ward–Thompson, Motte, & André 1999 as indicating that the cores are probably magnetically–supported and evolving through ambipolar diffusion to star formation (e.g. Lizano & Shu 1989; Basu & Mouschovias 1995). However, caution must be used with the above models because, as pointed out by André, Ward–Thompson & Motte 1996 and André, Ward–Thompson & Barsony 2000, they require fairly strong magnetic fields on parsec scales ( $\sim 100 \mu\text{m}$ ), difficult to reconcile with available Zeeman measurements (e.g. Crutcher 1999). Higher spatial resolution observations are needed to make quantitative conclusions on the column and volume density structure of star forming cores and better constrain theory.

In cores with stars,  $\alpha$  is typically greater than 2 (Tab. 6). This is probably due to an excitation temperature increase at the center caused by the presence of a sufficiently luminous protostar. A similar result (greater map “spikiness” of cores with stars over that of starless cores) was found by Mizuno et al. 1994 using  $\text{H}^{13}\text{CO}^+$  data. From Fig. 7 we also note that the model integrated intensity tends to overestimate data points at large impact parameters. This reflects the fast drop in  $T_{\text{ex}}$  caused by the density drop and it is well reproduced by Monte Carlo simulations. It is not related to the “sharp edges” found in isolated prestellar cores at radii  $> 15000$  AU (Bacmann et al. 2000).

To check the effects of optical depth in the observed shallow profiles, in those cores with  $\tau_{\text{TOT}}^3 > 10$  (L1498, L1489, and L483) we made integrated intensity profiles by using

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<sup>3</sup> $\tau_{\text{TOT}}$  is the sum of the peak optical depths of the seven hyperfine components

the area below the thinnest hyperfine component of  $\text{N}_2\text{H}^+(1-0)$  having the least optical depth ( $F_1, F = 1, 0 \rightarrow 1, 1$ ; Caselli, Myers & Thaddeus 1995). In Fig. 7, the dotted curves indicate these profiles, normalized so that the peak integrated intensity of the  $F_1, F = 1, 0 \rightarrow 1, 1$  component is the same as the peak integrated intensity of all the components. The dotted curves in the L1498, L1489, and L483 plots (Fig. 7) closely follow the data points, suggesting that optical depth effects are not affecting our conclusions.

In summary, the radial density profiles of starless cores in Fig. 7 present a consistent picture of “central flattening” where the shape of the profile is shallower at small radii than at large radii. The  $\text{N}_2\text{H}^+$  integrated intensity profile is modelled by a spherically symmetric density law  $n \sim r^{-\alpha}$  where  $\alpha = 1.2$  for  $r < r_{\text{break}}$  and  $\alpha = 2.0$  for  $r > r_{\text{break}} \sim 0.03$  pc. Cores with stars are better modelled with single power laws  $n \propto r^{-\alpha}$  with  $\alpha \geq 2$ . These results are the first to show central flattening in a significant sample of molecular line maps. In contrast to dust continuum maps, these maps offer the prospect of relating core density structure to core turbulence structure, in more detailed studies to be made in the future. The agreement between dust and  $\text{N}_2\text{H}^+$  profiles suggests that the molecular gas traced by the  $\text{N}_2\text{H}^+$  line is not significantly depleted in relation to the dust, unlike CO and CS (Caselli et al. 1999; Caselli et al. 2001a,b; Bergin et al. 2001; Tafalla et al. 2001).

### 3.6. Variation of $\Delta v$ across the cores

Goodman et al. 1998 described a physical picture of star-forming dense cores and their environs where the cores are “velocity coherent” regions of nearly constant line width. From  $\text{NH}_3$  maps, Barranco & Goodman 1998 found that within the interiors of dense cores, the line widths are roughly constant and appear to increase at the map edges. Although many theories of low mass star formation begin with an isothermal sphere having no turbulence (e.g. Shu 1977), the line width inside the coherent cores is not purely thermal. A clearly measurable turbulent component remains even in these “coherent” regions (Fuller & Myers 1992; Caselli & Myers 1995). The “transition to coherence” may occur because of a decrease in the magnetic field’s ability to control gas motions in regions of very low ionization (Mouschovias 1991; Myers 1997; Goodman et al. 1998; Myers 1998).

We have made a similar study with our  $\text{N}_2\text{H}^+$  maps in those cores having a sufficient number of high sensitivity spectra across the map to allow us to see systematic variations in line width, if they are present. In Fig. 8, integrated intensity contour maps of 9 cores selected to have at least 9 spectra with  $\Delta v / \sigma_{\Delta v} \geq 3$  and  $I / \sigma_I \geq 5$  are superposed on grey scale maps of line width (light grey indicates narrow lines). From the figure, it is evident that starless cores show a spotty pattern of low line width at central positions inside the

integrated intensity half-maximum contour, whereas more internal structure is present in cores with stars. In fact, L43 (Bence et al. 1998), L483 (Tafalla et al. 2000, Fuller & Wootten 2000, Park et al. 2000) and L1228 (Tafalla & Myers 1997) are associated with well known protostellar outflows, which may contribute to the broadening of  $\text{N}_2\text{H}^+$  line widths. However, in starless cores, the broadest lines are often located at the edges of the map. The positions indicated by dots on the maps in Fig. 8 are those where a good ( $\Delta v/\sigma_{\Delta v} \geq 3$ ) estimate of the intrinsic line width via hfs fitting was possible.

Another way of looking at core velocity structure is to consider plots similar to those shown by Goodman et al. 1998, where the intrinsic line width is reported as a function of the antenna temperature, which in turn is used as a measure of the distance from the peak of the map. Instead of using antenna temperature we consider the impact parameter  $b$ , already introduced in Sect. 3.5. In practice, at each map point  $i$  we associate an “effective radius”  $b(i)$  by counting the number of positions  $N_{\text{mp}}$  with integrated intensity  $I$  equal or larger than  $I(i)$ , so that  $b = \sqrt{(a \times N_{\text{mp}})/\pi}$ , where  $a$  is the area of the map pixel. Thus we can consider in more quantitative fashion how the line width varies with effective map radius. We point out that this way of looking at core coherence is equivalent to that described in Goodman et al. 1998 (we tried both methods for three cores and found essentially the same results), but this approach shows the dependence on size scale explicitly.

We first examine how core line widths vary with effective radius by fitting a simple linear relation between  $\Delta v$  and  $b$ . Table 7 (columns 2, 3, and 4) lists the intercept  $p$ , the slope  $q$ , and the correlation coefficient  $cc$  of the linear least squares fit to the  $\Delta v - b$  data for each core (only those cores with at least 9 positions having  $\Delta v/\sigma_{\Delta v} \geq 3$  and  $I/\sigma_I \geq 5$  are included in the table). From Tab. 7, three classes of cores are recognized: a) cores with a “significant” ( $cc \geq 0.4$ ) positive  $\Delta v - b$  correlation (L1498, L1495, L1524, L1400K, L260); b) cores with no significant correlation; and c) cores with a significant negative correlation (PER4, B5, TMC-1C2, L1174). Starless cores and cores with stars are found in all three classes. Fig. 9 shows some example of the three classes. Evidently the slight increase of single-tracer line width with effective map radius discussed by Goodman et al. 1998 is significant in a few cores, but these are not representative of the 22 cores in Tab. 7.

We next consider how the variation in line width relates to the mean line width, for all the usable spectra in the map. Columns 5 and 6 of Tab. 7, report for each core the average linewidth  $\langle \Delta v \rangle = (1/M) \times \sum_{i=1}^M \Delta v(i)$ , with  $M$  = number of positions in the map where  $\Delta v$  has been calculated), and the corresponding standard deviation of the sample population  $s_{\langle \Delta v \rangle} (\equiv (1/\sqrt{M-1}) \times \sqrt{\sum_{i=1}^M (\Delta v_i - \langle \Delta v \rangle)^2})$ . Note that  $\langle \Delta v \rangle$  is different from  $\Delta v$  of the average spectrum given in Tab. 2. The corresponding errors are reported in Appendix A.

These data can be compared with a simple statistical model of “cells” or “zones” along the line of sight to estimate the “coherence length” or length over which the motions are correlated along the line of sight (Kleiner & Dickman 1987). We assume that each cell moves as a coherent unit, with a velocity along the line of sight that follows a Gaussian probability distribution with the dispersion  $\sigma$  equal to the nonthermal component of the overall velocity distribution that we see in the line profile ( $\sigma^2 = \sigma_{\text{NT}}^2 = \Delta v^2 / (8 \ln 2) - kT/m_{\text{obs}}$ , where  $k$  is the Boltzmann constant,  $T$  is the kinetic temperature, and  $m_{\text{obs}}$  is the mass of the observed molecule). Then from basic statistics we can write relations for the rms of the line width and the rms of the mean velocity:

$$\sigma_{\langle \Delta v_{\text{NT}} \rangle} = \frac{\langle \Delta v_{\text{NT}} \rangle}{\sqrt{N}} \quad (11)$$

$$\sigma_{\langle v \rangle} = \frac{\sqrt{\langle \Delta v_{\text{NT}}^2 \rangle}}{\sqrt{8 \ln 2 N}} \quad (12)$$

where  $N$  is the typical number of cells along the line of sight. Figure 10 shows  $\sigma_{\langle \Delta v_{\text{NT}} \rangle}$  versus  $\langle \Delta v_{\text{NT}} \rangle$ . In the figure, thin lines represent eqn.( 11) for different  $N$  values. A linear least square fit to the data, taking into account the errors on  $\sigma_{\Delta v_{\text{NT}}}$ , gives  $N = 10$ , with a linear correlation coefficient  $cc = 0.9$ .

Relation (12) is investigated in Fig. 11, where the dispersion of the average velocity gradient fit residuals  $\langle V_{\text{LSR}} - V_{\text{fit}} \rangle$  is plotted versus the rms of the nonthermal line width  $\sqrt{\langle \Delta v_{\text{NT}}^2 \rangle}$ .  $V_{\text{fit}}$  is the velocity predicted by fitting a first-order gradient, so that  $V_{\text{LSR}} - V_{\text{fit}}$  can be used to analyse higher order structure in the velocity field. In this case, a linear least square fit to the data gives  $N = 13$ , with  $cc = 0.5$ . Only cores with at least 9 data points available to estimate means and standard deviations have been included in Fig. 10 and 11. L1251E has been excluded from the two figures because of the complex velocity structure clearly seen in Fig. 6, suggestive of two adjacent cores rotating in almost opposite directions.

In each of Fig. 10 and 11, there is a clear tendency for the “dispersion” quantity on the  $y$ -axis to correlate with the “mean” quantity on the  $x$ -axis. From this simple “cell” model we conclude that  $N \simeq 10$ . Given that the length along the line of sight to which our observations are sensitive is comparable to the map diameter, typically 0.1 pc, then the “coherence length” deduced from our data is about 0.01 pc. This size scale is comparable to the “cutoff” wavelength below which Alfvén waves cannot propagate because the neutral-ion collision frequency in the neutral medium becomes comparable to or less than the wave frequency (McKee & Zweibel 1995; Goodman et al. 1998):

$$\lambda_{\text{cut}}(\text{pc}) = 0.007 \frac{(B/10\mu\text{G})}{(x_i/5 \times 10^{-8})(n/10^5\text{cm}^{-3})^{3/2}}, \quad (13)$$

where  $B$  is the magnetic field strength,  $x_i$  is the ionization fraction ( $n_i/n$ ), and  $n$  is the volume density of the molecule of mean mass (2.33 amu). The choice of  $B \sim 10 \mu\text{G}$  is based on the OH Zeeman measurements in L1544 (a core in our sample) of Crutcher & Troland 2000. At the typical densities of the observed cores ( $\sim 10^5 \text{ cm}^{-3}$ , see Tab. 8), the ionization fraction is about  $5 \times 10^{-8}$ , if the standard relation between  $x_i$  and  $n(\text{H}_2)$  is used ( $x_i = 1.3 \times 10^{-5} n(\text{H}_2)^{-0.5}$ , McKee 1989<sup>4</sup>). Therefore, the “transition to coherence” may arise from insufficient wave coupling on size scales of  $\sim 0.01 \text{ pc}$ , as (i) proposed by Mouschovias 1991, (ii) elaborated by Myers (1997, 1998) as a reason why  $\text{NH}_3$  line widths are nearly thermal and narrower than their surrounding  $^{13}\text{CO}$  gas (as demonstrated by Fuller & Myers 1992 and Caselli & Myers 1995), and (iii) suggested by Goodman et al. 1998 as a reason why core line widths are “coherent” – nearly constant in the interior of  $\text{NH}_3$  maps. In general, the positive correlations shown in Fig. 10 and 11 strongly suggest the presence of internal motions, not ascribed to simple solid-body rotation and probably due to turbulence, which broaden lines and contribute to line width and LSR velocity dispersion across the cores.

To further quantify the “coherence” of core line widths, we ask whether the “local” dispersion of line widths at radius near  $b$ ,  $s_{\Delta v}$ , increases with  $b$  in  $\text{N}_2\text{H}^+$  cores. To answer this question, the standard deviation of the average  $\Delta v$  inside all the contour levels between 20% and 100% of the integrated intensity peak has been calculated (in steps determined by the following requirements: i) consecutive levels are associated with different impact parameters; ii) each level contains at least 5 positions). As with previous analysis, we only considered those positions where  $\Delta v/\sigma_{\Delta v} \geq 3$  and  $I/\sigma_{\text{I}} \geq 5$ . We then performed linear least square fits to the  $s_{\Delta v}$ – $b$  data in each core and the results are listed in columns 7, 8, and 9 of Tab. 7. Note that all the cores (with the exception of L1495, L1536, and L1512) show a strong positive correlation between the two quantities, indicating that dispersion is indeed increasing with projected radius. We tested whether the general increase in  $s_{\Delta v}$  with increasing  $b$  could be due to the corresponding decrease in signal-to-noise (S/N) ratio with increasing  $b$ . We raised the threshold  $(I/\sigma_{\text{I}})_{\text{min}}$  from 5 to 10 and repeated the linear least-square fits as in Tab. 7 with smaller, lower-noise data sets. For the 12 surviving cores with enough data points (at least 9), the tendency for  $s_{\Delta v}$  to increase with  $b$  is evident in 5 starless cores – L1544, L183, TMC-1CS, TMC-1NH3, TMC-2 – and 5 cores with stars – L1489, L43, L1228, L1221, L1251E. The remaining two cores show a negative (L1512) and a null (L483)  $s_{\Delta v}$  –  $b$  correlation.

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<sup>4</sup>We note that Caselli et al. 2001b have recently found a different  $x_i$ – $n(\text{H}_2)$  relation for the L1544 core:  $x_i = 5.2 \times 10^{-6} n(\text{H}_2)^{-0.56}$ , which, at  $n(\text{H}_2) = 10^5 \text{ cm}^{-3}$ , implies an electron fraction of  $8 \times 10^{-9}$ , six times lower than that deduced from the “standard” relation. With this new value of  $x_i$ , the “typical” cutoff wavelength is about 0.001 pc.

This analysis of 22 low-mass  $\text{N}_2\text{H}^+$  cores indicates that the brightest part of a core map has nearly constant line width, typically  $0.3\text{--}0.4 \text{ km s}^{-1}$ , while the surrounding positions with fainter emission have line widths with much greater variation. This confirms the conclusions of Barranco & Goodman 1998 based on 4  $\text{NH}_3$  core maps. However, our data show no significant increase in  $\text{N}_2\text{H}^+$  line width with effective map radius for the typical core, in contrast to the result of Barranco & Goodman 1998.

### 3.7. Map structure

The  $\text{N}_2\text{H}^+$  maps presented in Fig. 2 are generally similar in shape and orientation to the  $\text{NH}_3$  maps of BM89 and Ladd, Myers & Goodman 1994. This similarity is easily understood, since  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  are closely related chemically ( $\text{N}_2$  is the precursor molecule for both species). In cores with stars, the factor of  $\sim 2$  smaller size of the  $\text{N}_2\text{H}^+$  maps compared to its  $\text{NH}_3$  counterpart probably reflects both the higher critical density ( $\sim 2 \times 10^5 \text{ cm}^{-3}$  for  $\text{N}_2\text{H}^+$  compared to  $\sim 3 \times 10^4 \text{ cm}^{-3}$  for  $\text{NH}_3$ ) and the finer angular resolution ( $\sim 54''$  instead of  $\sim 83''$ ) and sampling ( $25''$  or  $50''$  instead of  $60''$ ) used in the  $\text{N}_2\text{H}^+$  observations.

To quantify the complexity of the projected map structure, we have counted the number of map "peaks" and "elongations" in each of the 59  $\text{N}_2\text{H}^+$  maps in this paper and in each of the 47  $\text{NH}_3$  maps in BM89 and in Ladd, Myers & Goodman 1994. Here a "peak" is a local maximum of integrated intensity which exceeds its surrounding valley by at least 3-sigma, and an "elongation" is an extension from the position of a peak by at least one beam, which does not terminate in a new peak. We find that the  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  maps have similar proportions of simple and complex structure. The fraction of "simple" maps with single peaks and no elongation is 0.64 for  $\text{NH}_3$  and 0.70 for  $\text{N}_2\text{H}^+$ . The fraction of maps with at least two peaks is 0.12 for  $\text{NH}_3$  and 0.07 for  $\text{N}_2\text{H}^+$ . Because of small number statistics, these  $\text{NH}_3$  and  $\text{N}_2\text{H}^+$  fractions are not significantly different. One might expect that more peaks per map would be seen in the finer-resolution  $\text{N}_2\text{H}^+$  observations than in the coarser-resolution  $\text{NH}_3$  observations, but this is not the case. We interpret this result as arising from the fact that the  $\text{N}_2\text{H}^+$  maps have both finer resolution and smaller spatial extent, each by about the same factor of 1.5. Thus some  $\text{N}_2\text{H}^+$  maps show two peaks where the  $\text{NH}_3$  map shows one, but other  $\text{N}_2\text{H}^+$  maps do not extend far enough to sense the second peak seen in the  $\text{NH}_3$  map. Although relatively few  $\text{N}_2\text{H}^+$  maps have more than one local maximum (14 of 57), we note that most cases with double peaks have peak-to-peak separation of only 1–2 FWHM beam diameters. Therefore these core maps are nearly as "clumpy" as the map resolution allows.

### 3.8. Overview of core parameters

An overview of the parameters determined in previous sections is presented in Table 8, for cores with stars and starless cores separately. Although the dispersion in large, cores associated with young stellar objects are typically more turbulent (non-thermal line widths are about 1.5 times larger), have larger sizes (factor of  $\sim 1.4$ ), and are more massive (factor of  $\sim 2$ ), than starless cores. Other quantities ( $T_{\text{ex}}$ ,  $N_{\text{TOT}}(\text{N}_2\text{H}^+)$ , aspect ratio,  $\mathcal{G}$ ,  $\beta$ , have very similar values in the two classes of cores, suggesting that there is not a definite separation between them, at least from the analysis of  $\text{N}_2\text{H}^+$  (1–0) lines at the present angular resolution.

## 4. Conclusions

We have mapped 57 low mass cores in the rotational transition  $J = 1 \rightarrow 0$  of the molecular ion  $\text{N}_2\text{H}^+$ , using the FCRAO antenna. This extensive mapping survey has allowed us to study physical properties of dense cores with an angular resolution about 1.5 times finer than previous ammonia maps from BM89. The main conclusions of this work are summarized below.

1. The excitation temperature of the  $\text{N}_2\text{H}^+$  (1–0) line is typically  $\sim 5$  K, indicating that  $\text{N}_2\text{H}^+$  lines are subthermally excited. The peak  $\text{N}_2\text{H}^+$  column density averaged over the whole sample is  $N(\text{N}_2\text{H}^+) \sim 7 \times 10^{12} \text{ cm}^{-2}$ , about two orders of magnitude less than  $N(\text{NH}_3)$  (BM89). There is a positive correlation between  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  column densities and excitation temperatures in starless cores, whereas in cores with stars the scatter is large and no significant correlations are found. Although this may partially be due to the difficulty in estimating the  $\text{N}_2\text{H}^+$ (1–0) total optical depth, the lack of correlation in cores with stars suggests a different chemical evolution of  $\text{NH}_3$  and  $\text{N}_2\text{H}^+$ . However, the good correlations between LSR velocities and line widths in the entire sample, indicates that the two tracers generally originate from the same regions.
2. The mean aspect ratios of the mapped sources is  $\sim 2$ . Starless cores have about the same linear sizes than those found with  $\text{NH}_3$  (1,1) maps. On the other hand, cores with stars have  $r(\text{NH}_3) \sim 2 \times r(\text{N}_2\text{H}^+)$ . This gives evidence that cores associated with young stellar objects are more centrally concentrated than starless cores and that  $\text{N}_2\text{H}^+$  (1–0) traces denser gas than  $\text{NH}_3$  (1,1).
3. In average, starless cores have virial and “excitation” masses  $M_{\text{vir}} \sim M_{\text{ex}} \sim 3 M_{\odot}$ , and are less massive than cores with stars ( $M_{\text{vir}} \sim M_{\text{ex}} \sim 8 M_{\odot}$ ). The  $M_{\text{ex}}/M_{\text{vir}}$  ratio averaged over the whole sample is  $\sim 1$ .

4. Typical values of velocity gradient magnitudes are  $\sim 2$  km/s/pc, both in cores with stars and starless cores. If the gradient represents rotation, the ratio  $\beta$  of rotational energy to gravitational energy ranges between  $\sim 10^{-4}$  and 0.07 so that rotation is not significant in the support of the core. Maps of “local” velocity gradients reveal the presence of complex internal motions that deviate strongly from a simple model of solid body rotation of the whole core.

5. Six out of nine spheroidal starless cores present central flattening in the integrated intensity profile. This is consistent with a spherically symmetric density law  $n(r) \sim r^{-\alpha}$  where  $\alpha = 1.2$  for  $r < r_{\text{break}}$  and  $\alpha = 2$  for  $r > r_{\text{break}}$ , with  $r_{\text{break}} \sim 0.03$  pc. Cores with stars are better modelled with single power law density profiles with  $\alpha \gtrsim 2$ . These results are in qualitative agreement with submillimeter continuum observations, suggesting that  $\text{N}_2\text{H}^+$  is not significantly depleted inside dense cores (unlike CO and CS).

6. Most  $\text{N}_2\text{H}^+$  cores are “coherent” in having more uniform line widths in their bright interior than in their faint periphery, as seen earlier in  $\text{NH}_3$  observations. The fluctuations in line width also increase significantly with mean line width. However this sample shows no significant tendency for the line widths themselves to increase with map radius – a few cores have positive and negative trends, while most have no significant trend. For 20 of 26 cores, the standard deviation of the average line width,  $s_{\Delta v}$ , increases with  $b$ , indicating that core line widths vary more with increasing radius as previously found by Barranco & Goodman 1998 and Goodman et al. 1998 using ammonia data. Yet, line widths  $\Delta v$  positively correlate with the impact parameter  $b$  in only 5 sources (L1498, L1495, L1524, L1400K, and L260). Four sources present negative correlations (PER4, B5, TMC–1C2, L1174). The remaining 17 cores do not show a significant  $\Delta v - b$  correlation.

7. The “coherence length” deduced from our data is about 0.01 pc, comparable to the cutoff wavelength below which Alfvén waves cannot propagate. Thus, the “transition to coherence” may arise from a decay of turbulence in the innermost parts of the cores, due to insufficient wave coupling, on size scales of  $\sim 0.01$  pc.

8. Although  $\text{N}_2\text{H}^+$  maps have finer angular resolution than  $\text{NH}_3$  maps, they do not show a more complex structure. The majority (70%) of the cores in our sample have “simple”  $\text{N}_2\text{H}^+$  maps, with single peaks and no elongation. Most cases with double-peaks have peak-to-peak separation of only 1–2 FWHM beam diameters.

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### A. Error expressions

The error on the volume density  $n_{\text{ex}}$  (see Sect. 3.3) is found by propagating the error in eqn.(8):

$$\sigma_{n_{\text{ex}}} = \left[ \left( n_{\text{cr}} \sigma_{T_{\text{ex}}} \frac{k}{h\nu} \frac{\tilde{T}_{\text{kin}}(\tilde{T}_{\text{kin}} - \tilde{T}_{\text{cb}})}{(\tilde{T}_{\text{kin}} - \tilde{T}_{\text{ex}})^2} \frac{\tilde{T}_{\text{ex}}^2 \exp(-h\nu/(kT_{\text{ex}}))}{T_{\text{ex}}^2} \frac{1 - e^{-3\tau}}{3\tau} \right)^2 + \left( \sigma_{\tau} \frac{n_{\text{ex}} 3\tau}{1 - e^{-3\tau}} \frac{e^{-3\tau}(3\tau + 1) - 1}{\tau} \right)^2 \right]^{1/2} \quad (\text{A1})$$

The errors on the average line width  $\langle \Delta v \rangle$  and the corresponding sample standard deviation  $s_{\Delta v}$  have been calculated with the following expressions (from the propagation of error):

$$\sigma_{\langle \Delta v \rangle} = \frac{\sqrt{\sum_i \sigma_{\Delta v(i)}^2}}{N}, \quad (\text{A2})$$

$$\sigma_{s_{\langle \Delta v \rangle}} = \frac{\sqrt{\sum_i \sigma_{\Delta v(i)}^2 (\Delta v(i) - \langle \Delta v \rangle)^2}}{s_{\langle \Delta v \rangle} (N - 1)}. \quad (\text{A3})$$

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Table 1.  $\text{N}_2\text{H}^+(1-0)$  map results: peak position ( $\Delta\alpha$ ,  $\Delta\delta$ ) and integrated intensity ( $I$ )

Core	RA(1950) <sup>a</sup>	Dec(1950) <sup>a</sup>	$\Delta\alpha$ ( $^{\circ}$ )	$\Delta\delta$ ( $^{\circ}$ )	$\Delta T_{\text{A,rms}}^*$ (K)	$I \pm \sigma_I^b$ (K km s <sup>-1</sup> )	N <sub>ch</sub> <sup>i</sup>	Map <sup>c</sup>	Area <sup>d</sup> (arcmin <sup>2</sup> )	IRAS <sup>h</sup>
PER4-A	03 <sup>h</sup> 26 <sup>m</sup> 31 <sup>s</sup> .7	31 <sup>°</sup> 17′13″	-2.49	0.84	0.16	1.64±0.09	91	B	85.7	n
PER4-B			-4.18	0.00	0.19	1.56±0.11				n
PER4-C			-3.32	-1.70	0.22	1.05±0.13				y
PER5	03 26 45.5	31 28 48	0.00	0.00	0.17	2.00±0.10	76	B	21.4	y
PER6	03 27 10.3	30 12 34	0.00	0.84	0.16	1.67±0.10	93	B	21.4	y
PER7	03 29 39.5	30 49 50	0.00	0.00	0.17	1.45±0.11	100	B	21.4	y
PER9 <sup>e</sup>	03 30 10.4	31 10 14	-0.88	0.04	0.19	1.17±0.11	84	B	21.4	y
B5	03 44 32.7	32 44 30	0.00	-1.69	0.19	1.99±0.12	95	B	42.8	y
L1389	04 00 38.0	56 47 59	0.00	0.00	0.17	1.11±0.10	84	B	21.4	y
L1489	04 01 45.0	26 10 33	0.42	0.00	0.16	2.11±0.10	98	N	21.4	y
L1498	04 07 50.0	25 02 13	0.42	-0.42	0.16	1.20±0.10	88	N	21.4	n
L1495	04 11 02.7	28 00 43	0.00	0.84	0.19	1.75±0.11	77	B	21.4	y
L1400G	04 21 12.1	54 12 20	...	...	0.18	...	...	B	21.4	n
B217	04 24 48.1	26 11 38	-0.88	0.04	0.19	2.03±0.11	85	B	64.3	n
L1524	04 26 22.3	24 28 36	0.00	0.00	0.18	1.51±0.10	81	B	42.8	y
L1400K	04 26 51.0	54 45 27	0.00	0.00	0.12	0.66±0.06	69	B	21.4	n
TMC-2A	04 28 54.0	24 26 27	0.00	0.00	0.16	1.87±0.10	100	B	21.4	n
TMC-2	04 29 41.2	24 20 09	0.86	-0.86	0.20	1.64±0.12	90	B	128.5	n
L1536	04 30 33.2	22 37 50	-1.69	-1.69	0.17	1.30±0.10	89	B	85.7	n
L1534 <sup>e</sup>	04 36 42.3	25 34 16	-3.32	1.77	0.19	1.62±0.11	90	B	42.8	y
L1527	04 36 49.3	25 57 16	0.00	0.00	0.17	1.25±0.10	91	B	21.4	y
TMC-1NH <sub>3</sub> <sup>e</sup>	04 38 19.0	25 42 30	-0.86	0.04	0.14	2.34±0.09	107	B	21.4	n
TMC-1C2 <sup>e</sup>	04 38 25.5	25 56 00	1.69	-1.69	0.17	1.34±0.10	80	B	21.4	n
TMC-1C <sup>e</sup>	04 38 34.5	25 55 00	0.00	-0.86	0.18	1.34±0.10	74	B	21.4	n
TMC-1CS <sup>e</sup>	04 38 38.9	25 35 00	-0.86	2.61	0.13	1.53±0.08	90	B	21.4	n
L1517B	04 52 07.2	30 33 18	0.00	0.00	0.19	1.05±0.10	74	B	21.4	n
L1512	05 00 54.4	32 39 00	-0.45	0.04	0.16	1.06±0.09	75	N	21.4	n
L1544	05 01 14.0	25 07 00	0.00	-0.42	0.12	1.75±0.09	158	N	21.4	n
L1582A	05 29 11.9	12 28 20	0.00	0.00	0.10	0.68±0.07	104	B	21.4	y
B35	05 41 45.3	09 07 40	0.00	0.00	0.14	1.48±0.09	90	B	21.4	y
L134A <sup>e</sup>	15 50 58.1	-04 26 36	0.00	0.00	0.14	0.68±0.08	79	B	21.4	n
L183 <sup>e</sup>	15 51 35.7	-02 40 54	-0.88	-2.41	0.21	1.95±0.11	73	B	85.7	n
L1681B-A	16 24 41.1	-24 35 32	-0.88	-0.86	0.26	1.81±0.16	98	B	42.8	n
L1681B-B			-3.32	0.87	0.25	1.98±0.15				n
L1696A	16 25 30.0	-24 12 32	0.00	0.84	0.27	1.60±0.18	109	B	21.4	n
L43	16 31 42.1	-15 40 50	0.42	0.42	0.19	3.57±0.13	109	N	21.4	y
L260 <sup>e</sup>	16 44 22.3	-09 30 02	0.00	0.00	0.16	0.74±0.08	65	B	21.4	y
L158	16 44 33.7	-13 54 03	0.00	0.00	0.24	0.97±0.14	85	B	21.4	y
L234A	16 45 21.0	-10 46 33	0.86	0.04	0.22	0.66±0.08	37	B	21.4	n
L234E <sup>e</sup>	16 45 23.0	-10 51 43	0.00	-0.86	0.25	0.69±0.13	74	B	21.4	n

Table 1—Continued

Core	RA(1950) <sup>a</sup>	Dec(1950) <sup>a</sup>	$\Delta\alpha$ ( $\iota$ )	$\Delta\delta$ ( $\iota$ )	$\Delta T_{A,\text{rms}}^*$ (K)	$I \pm \sigma_I$ <sup>b</sup> (K km s <sup>-1</sup> )	$N_{\text{ch}}$ <sup>i</sup>	Map <sup>c</sup>	Area <sup>d</sup> (arcmin <sup>2</sup> )	IRAS <sup>h</sup>
L63	16 47 21.0	-18 01 00	0.00	0.00	0.29	1.75±0.17	85	B	21.4	n
B68	17 19 36.0	-23 47 13	0.00	0.00	0.20	0.64±0.10	64	B	21.4	n
L483	18 14 50.5	-04 40 49	0.00	0.00	0.15	4.32±0.10	109	N	21.4	y
B133	19 03 25.3	-06 57 20	0.00	0.00	0.19	0.56±0.10	67	B	21.4	y
L778	19 24 26.4	23 52 37	0.00	-0.81	0.16	1.72±0.10	97	B	21.4	y
B335	19 34 35.3	07 27 34	0.00	0.00	0.14	1.70±0.09	106	N	21.4	y
L1152	20 35 19.6	67 42 13	0.00	0.00	0.20	1.40±0.11	79	B	21.4	y
L1155C	20 43 00.0	67 41 47	0.00	0.00	0.11	0.72±0.06	81	B	21.4	n
L1082C	20 50 19.5	60 07 15	0.42	0.00	0.19	1.39±0.11	83	N	21.4	y
L1082A <sup>f</sup>	20 52 20.7	60 03 14	0.00	0.00	0.12	0.67±0.07	82	B	21.4	y
L1228	20 58 11.0	77 24 00	0.41	0.00	0.16	3.85±0.11	117	N	21.4	y
L1174	20 59 46.3	68 01 04	-0.44	-0.04	0.20	2.23±0.15	131	N	21.4	y
BERN48	21 00 20.0	78 11 00	0.41	0.42	0.23	1.93±0.14	103	N	21.4	y
L1172A	21 01 45.0	67 42 13	0.00	0.84	0.19	1.58±0.12	98	B	21.4	y
B361	21 10 35.0	47 12 01	0.00	0.84	0.17	1.17±0.11	112	B	21.4	y
L1031C	21 44 35.6	47 04 20	...	...	0.14	...	...	B	21.4	y
L1031B	21 45 32.0	47 18 13	0.00	0.00	0.14	2.31±0.12	186	B	21.4	y
L1221	22 26 37.1	68 45 37	0.00	0.00	0.22	4.14±0.15	125	N	21.4	y
L1251A <sup>g</sup>	22 29 34.1	74 58 51	0.00	0.00	0.19	1.39±0.12	95	B	21.4	y
L1251C	22 34 37.5	75 02 32	0.88	0.80	0.18	1.91±0.12	111	B	21.4	y
L1251E	22 38 36.4	74 55 50	-3.38	-0.42	0.17	4.03±0.15	197	N	42.8	y
L1262	23 23 32.2	74 01 45	0.86	-0.04	0.15	1.64±0.10	111	B	21.4	y

<sup>a</sup>Coordinates of the (0,0) map position; they do not always correspond to the coordinates quoted in BM89.

<sup>b</sup>Integrated intensity at the peak position;  $\sigma_I = \Delta T_{A,\text{rms}}^* \times \sqrt{N_{\text{ch}}} \times \Delta v_{\text{res}}$ , where  $\Delta T_{A,\text{rms}}^*$  [K] is the 1  $\sigma$  level of the noise in the off-line channels,  $N_{\text{ch}}$  is the number of channels in the integrated intensity, and  $\Delta v_{\text{res}}$  [km s<sup>-1</sup>] is the velocity resolution (=0.063 km s<sup>-1</sup>).

<sup>c</sup>Type of map: B  $\equiv$  beam sampling; N  $\equiv$  Nyquist sampling.

<sup>d</sup>Mapped area.

<sup>e</sup>The half maximum contour extends over the mapped area.

<sup>f</sup>A second component is present in the West direction; it has not been included in the integrated intensity estimate.

<sup>g</sup>There is another peak in the mapped area which belongs to another core (whose half maximum contour extends outside the mapped area).

<sup>h</sup>IRAS association, from Jijina et al. 1999.

<sup>i</sup>Number of channels in integrated area.

Table 2.  $\text{N}_2\text{H}^+(1-0)$  map results: multicomponent (hfs) fit to the peak and averaged<sup>a</sup> spectrum.

Core	$V_{\text{LSR}}$ (km s <sup>-1</sup> )	$\Delta v$ (km s <sup>-1</sup> )	$\tau_{\text{TOT}}^{\text{b}}$	$T_{\text{ex}}^{\text{c}}$ (K)	$N_{\text{tot}} \times 10^{-12}$ (cm <sup>-2</sup> )
PER4-A <sup>d</sup>	7.60±0.02	0.58±0.06	0.1	5.0	4.7±0.6
	7.60±0.02	0.47±0.05	4±2	5±1	5±3
PER4-B	7.61±0.01	0.36±0.03	0.1	5.0	4.5±0.5
	7.565±0.007	0.36±0.01	0.1	5.0	3.5±0.1
PER4-C	7.38±0.02	0.33±0.04	0.1	5.0	3.0±0.4
	7.41±0.02	0.38±0.04	0.1	5.0	2.5±0.4
PER5	8.221±0.008	0.33±0.02	0.1	5.0	5.5±0.5
	8.203±0.006	0.29±0.02	5±2	5±1	5±2
PER6	5.87±0.01	0.44±0.03	0.1	5.0	4.8±0.4
	5.880±0.008	0.38±0.02	6±2	4.1±0.5	6±2
PER7	6.81±0.02	0.33±0.04	15±7	3.8±0.6	11±5
	6.82±0.02	0.45±0.05	5±3	3.9±0.8	5±3
PER9	6.91±0.02	0.41±0.04	0.1	5.0	3.4±0.4
	6.82±0.01	0.42±0.03	0.1	5.0	2.9±0.2
B5	10.31±0.02	0.47±0.03	0.1	5.0	6.0±0.5
	10.25±0.01	0.39±0.02	4±2	4.7±0.9	5±2
L1389	-4.65±0.03	0.49±0.05	0.1	5.0	3.2±0.4
	-4.60±0.01	0.33±0.04	7±3	3.9±0.7	5±3
L1489	6.80±0.01	0.28±0.02	17±7	4.3±0.8	13±5
	6.783±0.004	0.277±0.009	7±1	4.7±0.4	6±1
L1498	7.833±0.007	0.18±0.02	18±9	4.1±0.8	8±4
	7.840±0.002	0.191±0.005	11±1	3.9±0.2	4.7±0.6
L1495	6.832±0.007	0.22±0.02	4±3	7±3	5±3
	6.824±0.004	0.27±0.01	4±1	6±1	4±1
L1400G <sup>e</sup>	...	...	...	...	...
B217	7.02±0.01	0.34±0.03	4±3	6±3	6±4
	7.001±0.005	0.33±0.01	4±1	5.1±0.8	5±2
L1524	6.36±0.01	0.26±0.03	15±8	4.1±0.9	10±5
	6.339±0.008	0.35±0.02	9±2	3.7±0.3	7±2
L1400K	3.28±0.01	0.19±0.02	11±6	3.6±0.6	4±2
	3.300±0.006	0.24±0.01	6±2	3.6±0.3	3±1
TMC-2A	5.917±0.006	0.22±0.02	16±4	4.7±0.7	11±3
	5.935±0.006	0.27±0.01	9±2	4.2±0.4	7±2
TMC-2	6.26±0.02	0.40±0.03	0.1	5.0	4.9±0.5
	6.197±0.005	0.36±0.01	5±1	4.3±0.4	5±1

Table 2—Continued

Core	$V_{\text{LSR}}$ (km s <sup>-1</sup> )	$\Delta v$ (km s <sup>-1</sup> )	$\tau_{\text{TOT}}^{\text{b}}$	$T_{\text{ex}}^{\text{c}}$ (K)	$N_{\text{tot}} \times 10^{-12}$ (cm <sup>-2</sup> )
L1536	5.53±0.01	0.30±0.02	0.1	5.0	3.9±0.4
	5.649±0.003	0.263±0.009	6±1	4.2±0.3	3.9±0.8
L1534	6.40±0.01	0.36±0.02	0.1	5.0	4.6±0.4
	6.304±0.006	0.39±0.01	3±1	5±1	4±2
L1527	5.90±0.01	0.29±0.03	13±7	3.9±0.7	8±5
	5.922±0.008	0.34±0.02	9±2	3.6±0.3	6±2
TMC-1NH <sub>3</sub>	5.956±0.009	0.36±0.02	11±3	4.6±0.5	11±3
	5.955±0.004	0.39±0.01	5.6±0.8	4.6±0.3	6.2±0.9
TMC-1C2	5.27±0.02	0.29±0.03	14±6	3.9±0.7	9±4
	5.219±0.006	0.29±0.01	8±2	3.8±0.3	5±1
TMC-1C	5.27±0.02	0.27±0.04	18±10	3.8±0.8	11±6
	5.257±0.004	0.25±0.01	12±2	3.6±0.2	6±1
TMC-1CS	5.89±0.01	0.38±0.03	8±3	4.3±0.8	8±3
	5.853±0.005	0.41±0.01	4±1	4.3±0.4	5±1
L1517B	5.80±0.01	0.27±0.02	0.1	5.0	3.0±0.3
	5.830±0.008	0.22±0.02	9±4	4.0±0.6	5±2
L1512	7.108±0.007	0.18±0.02	5±3	5±2	3±2
	7.088±0.002	0.195±0.006	7±1	4.2±0.3	3.6±0.6
L1544	7.169±0.008	0.31±0.01	10±2	4.5±0.5	9±2
	7.162±0.003	0.307±0.006	8.1±0.9	4.0±0.2	6.0±0.7
L1582A <sup>f</sup>	10.20±0.02	0.43±0.05	0.1	5.0	1.9±0.3
	...	...	...	...	...
B35	11.69±0.04	0.61±0.08	9±4	3.6±0.5	12±6
	11.86±0.04	0.89±0.09	0.1	5.0	4.2±0.5
L134A	2.74±0.01	0.29±0.03	0.1	5.0	2.1±0.3
	2.764±0.009	0.34±0.02	0.1	5.0	1.4±0.1
L183	2.44±0.01	0.25±0.02	22±7	4.3±0.7	14±5
	2.422±0.004	0.303±0.009	8±1	4.1±0.2	6.1±0.9
L1681B-A	3.62±0.02	0.40±0.03	0.1	5.0	5.5±0.6
	3.69±0.02	0.45±0.04	0.1	5.0	3.8±0.4
L1681B-B	4.12±0.01	0.36±0.03	0.1	5.0	5.7±0.7
	4.13±0.01	0.39±0.04	0.1	5.0	3.9±0.5
L1696A	3.37±0.01	0.25±0.03	0.1	5.0	3.9±0.6
	3.40±0.01	0.30±0.02	0.1	5.0	2.9±0.3
L43	0.678±0.009	0.36±0.02	6±2	7±1	11±4

Table 2—Continued

Core	$V_{\text{LSR}}$ (km s <sup>-1</sup> )	$\Delta v$ (km s <sup>-1</sup> )	$\tau_{\text{TOT}}^{\text{b}}$	$T_{\text{ex}}^{\text{c}}$ (K)	$N_{\text{tot}} \times 10^{-12}$ (cm <sup>-2</sup> )
L260	0.692±0.003	0.396±0.007	5.9±0.5	5.4±0.3	8.6±0.8
	3.503±0.008	0.20±0.02	0.1	5.0	2.2±0.3
	3.480±0.005	0.19±0.01	11±3	3.4±0.2	4±1
L158 <sup>f</sup>	3.91±0.01	0.23±0.04	0.1	5.0	2.7±0.5
	...	...	...	...	...
L234A	2.95±0.01	0.21±0.02	0.1	5.0	2.3±0.3
	2.936±0.007	0.23±0.02	0.1	5.0	1.9±0.2
L234E <sup>g</sup>	...	...	...	...	...
	3.04±0.02	0.30±0.04	12±7	3.2±0.3	7±4
L63	5.78±0.01	0.21±0.03	13±6	5±1	8±4
	5.780±0.007	0.27±0.02	9±2	4.3±0.5	6±2
B68	3.35±0.02	0.27±0.04	0.1	5.0	1.9±0.4
	3.38±0.02	0.33±0.05	0.1	5.0	1.4±0.3
L483	5.53±0.01	0.59±0.03	16±3	4.6±0.4	27±5
	5.432±0.004	0.495±0.008	11.6±0.7	4.5±0.1	16±1
B133 <sup>h</sup>	12.1±0.2	0.9±0.3	0.1	5.0	2±1
	...	...	...	...	...
L778	9.98 ±0.02	0.44±0.04	6±3	4.4±0.9	7±4
	9.944±0.009	0.40±0.02	5±2	4.4±0.7	5±2
B335	8.36±0.01	0.39±0.03	6±3	4.5±0.9	6±3
	8.345±0.008	0.40±0.02	7±2	4.0±0.4	6±2
L1152	2.70±0.02	0.46±0.04	0.1	5.0	4.2±0.6
	2.60±0.02	0.48±0.03	0.1	5.0	2.8±0.2
L1155C	2.69±0.02	0.36±0.04	7±4	3.6±0.5	5±3
	2.70±0.01	0.33±0.03	6±3	3.5±0.4	4±2
L1082C	-2.53±0.02	0.42±0.04	0.1	5.0	3.8±0.5
	-2.55±0.01	0.33±0.03	16±6	3.4±0.3	10±4
L1082A	-2.13±0.02	0.35±0.04	0.1	5.0	1.9±0.3
	-2.19±0.02	0.46±0.04	0.1	5.0	1.7±0.2
L1228	-8.06±0.02	0.61±0.04	9±2	4.9±0.6	18±4
	-8.041±0.008	0.68±0.02	5.9±0.8	4.5±0.3	11±2
L1174	2.67±0.06	1.2±0.2	0.1	5.0	7±1
	2.66±0.02	1.05±0.06	0.1	5.0	4.8±0.4
BERN48	-7.35±0.03	0.54±0.06	0.1	5.0	5.4±0.8
	-7.34±0.01	0.46±0.04	4±2	5±1	5±3

Table 2—Continued

Core	$V_{\text{LSR}}$ (km s <sup>-1</sup> )	$\Delta v$ (km s <sup>-1</sup> )	$\tau_{\text{TOT}}^{\text{b}}$	$T_{\text{ex}}^{\text{c}}$ (K)	$N_{\text{tot}} \times 10^{-12}$ (cm <sup>-2</sup> )
L1172A	2.91±0.04	0.54±0.09	8±5	3.8±0.7	10±6
	2.88±0.02	0.50±0.04	8±3	3.7±0.4	9±3
B361	2.78±0.05	0.70±0.09	0.1	5.0	3.5±0.6
	2.64±0.04	0.9±0.2	5±3	3.3±0.3	9±5
L1031C <sup>e</sup>	...	...	...	...	...
L1031B	4.18±0.05	1.6±0.2	0.1	5.0	7.0±0.9
	3.91±0.03	1.1±0.1	0.1	5.0	4.6±0.6
L1221	-4.42±0.02	0.67±0.05	6±2	6±1	15±5
	-4.430±0.009	0.69±0.02	6.9±0.9	4.5±0.3	13±2
L1251A	-3.93±0.02	0.45±0.05	0.1	5.0	4.1±0.6
	-3.93±0.01	0.36±0.04	8±4	3.8±0.6	6±3
L1251C	-4.71±0.01	0.29±0.03	12±5	4.3±0.9	9±4
	-4.75±0.02	0.55±0.06	4±3	3.9±0.9	6±4
L1251E	-3.93±0.03	1.35±0.08	0.1	5.0	11.8±0.8
	-3.872±0.009	1.50±0.02	0.1±0.1	5.0	7.8±0.2
L1262	4.11±0.01	0.39±0.05	18±10	3.8±0.8	15±9
	4.06±0.01	0.43±0.02	8±2	3.8±0.3	8±2

<sup>a</sup>The averaged spectrum is obtained by adding together all the spectra inside the half maximum contour.

<sup>b</sup> $\tau_{\text{TOT}}$  is the sum of the peak optical depth of the seven hyperfine components.

<sup>c</sup>Excitation temperature calculated by assuming a main beam efficiency  $\eta_{\text{B}}=0.51$ . If  $\tau_{\text{TOT}} < 1$ ,  $T_{\text{ex}} = 5$  K has been assumed (see text).

<sup>d</sup>The first row refers to the peak spectrum, whereas the second row refers to the averaged spectrum.

<sup>e</sup>No detection.

<sup>f</sup>Compact source: only one spectrum inside the half maximum contour.

<sup>g</sup>Individual spectra cannot be hfs-fitted because of low S/N.

<sup>h</sup>Only the peak spectrum can be hfs-fitted because of low S/N in the other map spectra.

Table 3. Angular and linear size of  $\text{N}_2\text{H}^+(1-0)$  cores

Core <sup>a</sup>	PA <sup>b</sup> (deg)	Major <sup>c</sup> (arcmin)	Minor (arcmin)	Aspect Ratio	$r^d$ (arcmin)	$r$ (pc)	D <sup>e</sup> (pc)
PER4-A <sup>f</sup>	45	3.4	0.5	6.4	0.7	0.069	350
PER4-B <sup>f</sup>	98	3.9	0.8	4.6	0.9	0.092	350
PER4-C	22	2.0	1.3	1.6	0.8	0.08	350
PER5	59	2.2	1.3	1.7	0.8	0.09	350
PER6	64	3.1	1.5	2.0	1.1	0.11	350
PER7	40	1.7	1.0	1.6	0.7	0.07	350
PER9	71	1.8	1.1	1.7	0.7	0.07	350
B5	<sup>f</sup> 98	3.9	0.9	4.3	0.9	0.095	350
L1389 <sup>f</sup>	22	1.2	0.5	2.5	0.4	0.065	600
L1489	135	1.6	1.1	1.4	0.7	0.027	140
L1498	121	2.6	2.0	1.4	1.1	0.046	140
L1495	115	2.9	1.9	1.5	1.2	0.048	140
B217	58	2.7	1.6	1.7	1.0	0.042	140
L1524	71	5.3	1.8	2.9	1.6	0.064	140
L1400K	35	2.9	1.8	1.6	1.2	0.057	170
TMC-2A	89	2.0	1.4	1.4	0.8	0.034	140
TMC-2	53	5.3	3.8	1.4	2.2	0.091	140
L1536	162	5.5	3.2	1.7	2.1	0.085	140
L1534	147	5.7	2.0	2.8	1.7	0.069	140
L1527	19	2.5	1.9	1.3	1.1	0.044	140
L1517B	165	1.6	1.4	1.1	0.7	0.030	140
L1512	114	2.3	1.6	1.5	1.0	0.039	140
L1544	125	2.0	1.2	1.7	0.8	0.032	140
L1582A <sup>f</sup>	19	1.2	0.5	2.5	0.4	0.046	400
B35	<sup>f</sup> 3	1.8	0.9	2.1	0.6	0.072	400
L134A	121	3.3	2.0	1.7	1.3	0.060	160
L1681B-A	146	2.3	1.0	2.2	0.8	0.036	160
L1681B-B	162	2.4	1.1	2.2	0.8	0.039	160
L1696A	34	2.3	1.3	1.8	0.9	0.040	160
L43	172	3.0	1.6	1.9	1.1	0.050	160
L260	38	3.7	2.1	1.8	1.4	0.065	160
L158	<sup>f</sup> 112	0.9	0.8	1.2	0.4	0.020	160
L234A	45	3.6	1.2	3.0	1.0	0.048	160
L63	94	3.7	1.9	1.9	1.3	0.062	160
B68	97	2.1	1.1	1.9	0.8	0.044	200
L483	47	1.5	1.2	1.2	0.7	0.040	200
B133	30	1.3	1.0	1.3	0.6	0.101	600
L778	148	2.0	1.6	1.2	0.9	0.109	420
B335 <sup>f</sup>	78	0.7	0.3	2.1	0.2	0.018	250
L1152	<sup>f</sup> 46	3.4	0.9	3.6	0.9	0.115	440

Table 3—Continued

Core <sup>a</sup>	PA <sup>b</sup> (deg)	Major <sup>c</sup> (arcmin)	Minor (arcmin)	Aspect Ratio	$r^d$ (arcmin)	$r$ (pc)	D <sup>e</sup> (pc)
L1155C	80	1.7	1.1	1.6	0.7	0.088	440
L1082C	<sup>f</sup> 45	1.2	0.8	1.6	0.5	0.062	440
L1082A	81	1.6	1.2	1.3	0.7	0.092	440
L1228	95	1.5	1.0	1.5	0.6	0.055	300
L1174	165	1.3	1.0	1.3	0.6	0.072	440
BERN48 <sup>f</sup>	8	1.3	0.5	2.9	0.4	0.023	200
L1172A	28	1.7	1.5	1.2	0.8	0.100	440
B361	156	2.7	1.6	1.7	1.1	0.108	350
L1031B	133	1.5	1.0	1.5	0.6	0.164	900
L1221	126	1.8	1.0	1.8	0.7	0.039	200
L1251A	58	2.7	1.4	2.0	1.0	0.056	200
L1251C	45	1.8	1.3	1.4	0.7	0.043	200
L1251E	1	5.2	1.8	2.9	1.5	0.088	200
L1262	155	2.1	1.4	1.5	0.9	0.050	200

<sup>a</sup>Six cores do not appear in this table because their half maximum contours extend beyond the mapped area: TMC–1NH<sub>3</sub>, TMC–1C2, TMC–1C, TMC–1CS, L183, and L234E. In the cases of L1534, L134A, and L260 it was possible to fit the core with a 2D Gaussian because only a small fraction of the half maximum contour lies beyond the mapped area.

<sup>b</sup>The position angle PA is defined as the angle in a clockwise direction from the positive right ascension axis.

<sup>c</sup>The major and minor axes have been corrected for beam size.

<sup>d</sup> $r$  is the half-power radius, 0.5 times the geometric mean of the major and minor axis. Note that  $r = R/2$ , where  $R$  is the size listed in Tab. 5 of BM89.

<sup>e</sup>Distance references are listed in BM89, Ladd et al. (1994), GBF93, Jijina et al. (1999).

<sup>f</sup>These cores have deconvolved sizes similar to the beam size, so their small sizes are less certain than the sizes of the larger sources because of beam subtraction.

Table 4. Volume Density and Mass

Core	$n_{\text{vir}}^{\text{a}}$ ( $10^4 \text{ cm}^{-3}$ )	$M_{\text{vir}}^{\text{a}}$ ( $M_{\odot}$ )	$\text{X}(\text{N}_2\text{H}^+)^{\text{b}}$ ( $10^{-10}$ )	$n_{\text{ex}}^{\text{c}}$ ( $10^4 \text{ cm}^{-3}$ )	$M_{\text{ex}}^{\text{c}}$ ( $M_{\odot}$ )
PER4-A	10±1	8±1	1.9±0.4	15±11	15±11
PER4-B	3.2±0.3	6.0±0.5	4.1±0.6	23	49
PER4-C	3.9±0.4	4.9±0.5	2.6±0.5	23	32
PER5	3.2±0.2	5.3±0.2	5.0±0.5	18±8	30±14
PER6	2.8±0.2	8.6±0.6	4.3±0.5	8±3	28±10
PER7	5.6±0.5	4.1±0.4	8±4	4±2	4±1
PER9	6.0±0.6	5.3±0.5	2.2±0.3	23	23
B5	3.9±0.3	8.1±0.6	4.4±0.5	15±8	35±19
L1389	9±1	5.7±0.7	1.5±0.3	7±4	6±4
L1489	32±1	1.47±0.06	4±2	13±3	0.7±0.1
L1498	8.8±0.3	2.08±0.07	5±3	5.7±0.7	1.4±0.2
L1495	8.8±0.3	2.33±0.09	3±2	28±14	8±4
B217	15±1	2.6±0.2	3±2	20±8	4±2
L1524	5.4±0.3	3.3±0.2	7±4	5±1	3.1±0.8
L1400K	5.9±0.2	2.61±0.09	3±2	5±2	2.3±0.7
TMC-2A	17.7±0.7	1.64±0.06	5±1	8±2	0.8±0.2
TMC-2	3.6±0.3	6.5±0.5	4.0±0.5	11±3	20±5
L1536	3.3±0.1	4.9±0.2	3.8±0.4	10±2	14±3
L1534	5.7±0.3	4.5±0.2	3.2±0.3	23±13	19±10
L1527	12.0±0.8	2.5±0.2	4±2	4±1	0.9±0.3
TMC-1NH3	...	...	...	13±2	...
TMC-1C2	...	...	...	6±1	...
TMC-1C	...	...	...	3.8±0.6	...
TMC-1CS	...	...	...	11±3	...
L1517B	25±1	1.61±0.07	1.1±0.1	7±3	0.5±0.2
L1512	12.5±0.4	1.74±0.06	2±1	9±2	1.3±0.2
L1544	23.8±0.5	1.87±0.04	3.1±0.7	7±1	0.60±0.08
L1582A	16±2	3.5±0.4	0.7±0.1	23	8
B35	9±2	8±1	5±2	4±2	4±2
L134A	6.6±0.4	3.3±0.2	1.4±0.2	23	12
L183	...	...	...	8±1	...
L1681B-A	24±2	2.6±0.2	1.8±0.2	23	3
L1681B-B	18±1	2.5±0.2	2.2±0.3	23	4
L1696A	13.3±0.8	2.1±0.1	2.0±0.3	23	4
L43	11.0±0.5	3.3±0.2	6±2	22±3	6.8±0.9
L260	4.6±0.2	3.0±0.1	2.0±0.3	3.0±0.7	2.0±0.5
L158	50±4	1.00±0.08	0.7±0.2	23	0.6
L234A	8.7±0.3	2.27±0.08	1.5±0.2	23	7
L234E	...	...	...	1.9±0.8	...
L63	5.2±0.3	2.9±0.2	7±4	9±3	5±2

Table 4—Continued

Core	$n_{\text{vir}}^{\text{a}}$ ( $10^4 \text{ cm}^{-3}$ )	$M_{\text{vir}}^{\text{a}}$ ( $M_{\odot}$ )	$X(\text{N}_2\text{H}^+)^{\text{b}}$ ( $10^{-10}$ )	$n_{\text{ex}}^{\text{c}}$ ( $10^4 \text{ cm}^{-3}$ )	$M_{\text{ex}}^{\text{c}}$ ( $M_{\odot}$ )
B68	12±1	2.3±0.2	1.0±0.2	23	5
L483	29±2	4.5±0.3	6±1	9.3±0.5	1.55±0.08
B133	8±5	19±12	0.7±0.6	23	65
L778	2.8±0.3	8.6±0.8	6±3	12±5	39±18
B335	89±6	1.27±0.09	1.1±0.5	8±2	0.21±0.06
L1152	2.6±0.2	9.5±0.9	3.7±0.6	23	93
L1155C	3.6±0.3	5.7±0.5	4±3	4±2	8±4
L1082C	8.2±0.8	4.7±0.4	2.0±0.3	2.5±0.7	1.7±0.5
L1082A	3.2±0.3	5.9±0.5	1.8±0.3	23	47
L1228	16±1	6.4±0.6	5±1	12±2	5.4±0.9
L1174	26±7	23±6	0.9±0.3	23	24
BERN48	79±11	2.3±0.3	0.8±0.2	15±10	0.6±0.4
L1172A	4.1±0.8	10±2	6±4	5±2	13±5
B361	5±1	15±3	1.7±0.4	3±2	10±5
L1031B	9±2	95±18	1.3±0.3	23	276
L1221	36±4	5.2±0.6	3±1	12±2	1.8±0.3
L1251A	11±1	4.5±0.5	1.8±0.4	6±3	3±1
L1251C	12.4±0.8	2.4±0.2	4±2	8±4	1.7±0.8
L1251E	23±2	37±4	1.6±0.2	23	39
L1262	12±1	3.5±0.4	7±4	6±1	1.9±0.5

<sup>a</sup> $n_{\text{vir}}$  and  $M_{\text{vir}}$  is the virial volume density and mass, respectively. Data are not reported for those cores where the size cannot be determined.

<sup>b</sup>Fractional abundance of  $\text{N}_2\text{H}^+$  ( $X(\text{N}_2\text{H}^+) = N(\text{N}_2\text{H}^+)/N(\text{H}_2)$ ) calculated from  $n_{\text{vir}}$  and assuming a uniform sphere with  $N(\text{H}_2) = 4/3 n_{\text{vir}}/1.1 r$  (the factor 1.1 is to convert  $n$  to  $n(\text{H}_2)$ ).

<sup>c</sup>Volume density and mass coming from the density to critical density ( $n_{\text{cr}} = 2 \times 10^5 \text{ cm}^{-3}$ ; Ungerechts et al. 1997, ApJ, 482, 245) ratio, calculated by using equation (43) in Genzel 1992. Values with no associated errors imply an assumed  $T_{\text{ex}}$  value (= 5 K). The excitation temperature and the optical depth of the “averaged” or the “peak” spectrum (see Table 2) have been used, whichever has the smallest error. In the calculation,  $T_{\text{kin}} = 10 \text{ K}$  and  $T_{\text{bb}} = 2.7 \text{ K}$ .

Table 5. Results of Gradient Fitting

Core	Number of points	$\mathcal{G}$ (km/s/pc)	$\Theta_{\mathcal{G}}$ (deg E of N)	$\mathcal{G} \times r$ (km/s)	$\beta^a$ ( $10^{-3}$ )	$\langle V_{\text{LSR}} - V_{\text{fit}} \rangle^b$ (km/s)	$s_{\langle V_{\text{LSR}} - V_{\text{fit}} \rangle}^b$ (km/s)
PER4	10	0.64±0.05	-17±6	...	...	-0.01±0.01	0.07±0.01
B5	11	0.86±0.08	84±2	0.082	9.2	0.015±0.007	0.07±0.01
L1489	19	0.7±0.1	110±12	0.018	0.74	0.004±0.004	0.02±0.01
L1498	26	0.5±0.1	9±10	0.024	1.4	-0.002±0.003	0.013±0.003
L1495	9	0.9±0.2	87±8	0.045	4.5	0.004±0.006	0.046±0.008
B217	11	2.2±0.2	36±4	0.093	16	0.024±0.008	0.060±0.008
L1524	9	1.8±0.3	22±11	0.11	29	0.012±0.009	0.03±0.01
L1400K	10	1.8±0.1	62±4	0.10	27	0.000±0.005	0.019±0.006
TMC-2	24	0.7±0.1	86±7	0.067	6.6	-0.018±0.009	0.093±0.009
L1536	21	2.11±0.07	-7±1	0.18	66	-0.002±0.004	0.041±0.004
L1534	15	2.5±0.2	25±3	0.17	53	-0.011±0.007	0.083±0.008
TMC-1NH3	16	5.98±0.08	35.1±0.7	...	...	-0.008±0.005	0.159±0.006
TMC-1C2	14	1.25±0.09	94±6	...	...	0.004±0.005	0.036±0.007
TMC-1C	15	0.8±0.1	-136±10	...	...	0.004±0.005	0.040±0.005
TMC-1CS	17	2.7±0.2	44±3	...	...	-0.003±0.006	0.030±0.008
L1512	28	1.41±0.07	166±3	0.054	7.7	-0.002±0.002	0.017±0.003
L1544	32	1.0±0.1	-171±5	0.032	2.0	0.011±0.003	0.033±0.003
L183	35	1.19±0.08	-55±3	...	...	-0.006±0.003	0.055±0.005
L43	42	2.72±0.06	127±2	0.13	33	-0.022±0.003	0.045±0.004
L260	9	0.1±0.1	86±94	0.0078	0.11	-0.022±0.007	0.04±0.01
L483	44	2.38±0.06	63±2	0.096	9.5	0.022±0.004	0.063±0.004
B335	10	0.1±0.3	-58±187	0.0014	0.005	-0.005±0.008	0.021±0.009
L1228	43	2.2±0.1	-64±2	0.12	15	0.048±0.009	0.10±0.01
L1174	13	4.0±0.2	-158±4	0.29	30	0.01±0.02	0.08±0.03
L1221	22	3.2±0.3	-138±5	0.13	14	0.02±0.01	0.07±0.01
L1251E	90	1.66±0.06	-129±3	0.15	5.8	-0.175±0.007	0.355±0.006

<sup>a</sup> $\beta$  is the ratio of rotational kinetic energy to gravitational energy (see equation 6 of Goodman et al. 1993). Assuming  $\rho_0 = m \times n_{\text{vir}}$ , with  $m = 2.33$  amu, and  $n_{\text{vir}} \equiv$  volume density from Table 4,  $\beta = 4.86 \times 10^2 < \mathcal{G}^2 > / n_{\text{vir}}$  with  $\mathcal{G}$  in km/s/pc.

<sup>b</sup>Average value (and relative standard deviation) of the fit residuals  $V_{\text{LSR}}(i) - V_{\text{fit}}(i)$  across the core, where  $V_{\text{fit}}(i)$  is the LSR velocity at position  $(\alpha(i), \delta(i))$  determined by the least square fit of a velocity gradient.

Table 6. Integrated intensity profiles

Core	$\alpha$	$\chi_1^2$ ( $\times 10^2$ )	$b_{\text{break}}$ (pc)	$\chi_2^2$ ( $\times 10^2$ )
Cores with stars				
PER6	1.9	5.8	0.051	3.7
L1489	2.2	0.65	$<0.007^{\text{a}}$	8.7
L1495	1.9	3.4	0.024	1.3
L43	1.8	31	0.019	23
L483	2.2	23	$<0.010$	55
L1082C	2.5	0.24	$<0.021$	9.4
L1228	2.8	23	$<0.015$	220
L1174	2.2	0.61	$<0.021$	8.8
L1221	2.1	22	$<0.010$	28
Starless cores				
L1498	1.8	2.4	0.014	3.0
B217	1.9	1.9	0.020	0.86
L1400K	1.9	0.32	0.021	0.33
TMC-2	1.7	15	0.041	6.5
L1536	1.6	16	0.037	3.0
L1512	1.9	6.4	0.020	3.3
L1544	1.9	2.1	0.014	0.96
L63	1.8	13	0.031	4.8

<sup>a</sup>The smallest  $\chi^2$  is obtained with the smallest  $b_{\text{break}}$  ( $10''$ ), indicating that the profile is consistent with a single power law (see text for details).

Table 7. Variation of  $\Delta v$  across the cores

Core	$p^a$ (km s <sup>-1</sup> )	$q^a$ (km s <sup>-1</sup> pc <sup>-1</sup> )	$cc$	$\langle \Delta v \rangle^b$ (km s <sup>-1</sup> )	$s_{\langle \Delta v \rangle}^b$ (km s <sup>-1</sup> )	$p'^c$ (km s <sup>-1</sup> )	$q'^c$ (km s <sup>-1</sup> pc <sup>-1</sup> )	$cc'$
PER4	0.43±0.04	-0.9±0.4	-0.43	0.37±0.02	0.10±0.03	0.2±0.1	-0.4±0.9	-0.91
B5	0.48±0.03	-1.8±0.3	-0.72	0.33±0.01	0.09±0.02	0.04±0.05	0.4±0.4	0.91
L1489	0.24±0.02	1.4±0.7	0.30	0.298±0.008	0.06±0.02	0.03±0.01	0.2±0.4	0.23
L1498	0.19±0.01	1.2±0.4	0.41	0.235±0.006	0.038±0.009	0.008±0.010	0.8±0.3	0.81
L1495	0.21±0.03	2.0±0.8	0.53	0.29±0.01	0.05±0.01	0.05±0.06	0±1	0.11
B217	0.33±0.03	-0.5±0.8	-0.14	0.33±0.01	0.07±0.02	-0.01±0.05	1±1	0.68
L1524	0.24±0.04	2±1	0.52	0.34±0.02	0.07±0.02	0.1±0.1	-1±2	-0.95
L1400K	0.18±0.03	1.3±0.6	0.80	0.24±0.01	0.02±0.01	0.04±0.04	-0.3±0.8	-0.92
TMC-2	0.35±0.03	-0.7±0.5	-0.14	0.40±0.01	0.11±0.02	0.01±0.02	1.4±0.4	0.88
L1536	0.25±0.02	-0.2±0.3	-0.08	0.248±0.007	0.044±0.008	0.04±0.01	0.1±0.2	0.20
L1534	0.38±0.03	-0.7±0.6	-0.25	0.36±0.01	0.05±0.01	0.00±0.02	0.7±0.4	0.91
TMC-1NH3	0.40±0.02	-1.3±0.4	-0.30	0.39±0.01	0.13±0.02	-0.08±0.03	3.2±0.5	0.79
TMC-1C2	0.34±0.03	-1.5±0.6	-0.60	0.282±0.009	0.04±0.01	0.01±0.03	0.6±0.6	0.54
TMC-1C	0.26±0.03	0.1±0.6	0.03	0.29±0.01	0.05±0.01	0.03±0.03	0.5±0.5	0.54
TMC-1CS	0.38±0.03	0.2±0.6	0.06	0.40±0.01	0.07±0.02	0.03±0.03	0.5±0.6	0.62
L1512	0.17±0.01	0.8±0.4	0.29	0.202±0.005	0.033±0.006	0.019±0.007	0.3±0.2	0.70
L1544	0.30±0.01	-0.1±0.4	-0.03	0.303±0.006	0.043±0.008	0.017±0.007	0.6±0.2	0.82
L183	0.23±0.01	0.7±0.3	0.29	0.282±0.008	0.06±0.01	-0.005±0.009	0.9±0.2	0.85
L43	0.27±0.01	1.7±0.3	0.30	0.394±0.007	0.11±0.01	0.031±0.006	1.2±0.1	0.84
L260	0.18±0.03	1.3±0.8	0.51	0.24±0.01	0.05±0.02	-0.01±0.08	1±2	0.59
L483	0.40±0.01	-0.4±0.3	-0.07	0.45±0.01	0.15±0.02	0.067±0.009	1.0±0.2	0.65
B335	0.43±0.04	-1±1	-0.27	0.39±0.02	0.07±0.02	0.05±0.08	0±2	0.43
L1228	0.65±0.03	-0.7±0.4	-0.16	0.68±0.02	0.19±0.02	0.12±0.02	0.7±0.3	0.61
L1174	1.2±0.1	-9±2	-0.73	0.81±0.04	0.36±0.07	0.4±0.3	0±3	0.49
L1221	0.70±0.04	-2±1	-0.24	0.69±0.02	0.15±0.04	0.00±0.04	3±1	0.90
L1251E	0.90±0.02	-3.0±0.3	-0.31	0.93±0.02	0.34±0.02	0.25±0.01	1.0±0.1	0.80

<sup>a</sup> $p$  is the intercept and  $q$  is the slope of the best-fit linear  $\Delta v - b$  relation in each core (see text).

<sup>b</sup>Average linewidth and corresponding standard deviation.

<sup>c</sup> $p'$  is the intercept and  $q'$  is the slope of the  $s_{\Delta v} - b$  relation in each core (see text).

Table 8. Statistics on cores with and without stars

Parameter	Cores with Stars			Starless Cores		
	Mean	Standard Deviation	Number of Cores	Mean	Standard Deviation	Number of Cores
$\Delta v_{\text{NT}}$ (km s <sup>-1</sup> ) <sup>a</sup>	0.5	0.3	35	0.3	0.1	25
$T_{\text{ex}}$ (K)	5	1	15	4.4	0.8	14
$N_{\text{TOT}}(\text{N}_2\text{H}^+) (10^{12} \text{ cm}^{-2})$	8	5	35	6	3	25
$r$ (pc)	0.07	0.03	22	0.05	0.02	13
Aspect ratio	1.9	0.7	35	2	1	19
$n_{\text{vir}} (10^5 \text{ cm}^{-3})$	2	2	34	1.2	0.7	19
$M_{\text{vir}} (M_{\odot})$	9	16	34	3	2	19
$n_{\text{ex}} (10^5 \text{ cm}^{-3})$	0.9	0.7	21	0.8	0.4	17
$M_{\text{ex}} (M_{\odot})$	8	11	21	3	6	17
$X(\text{N}_2\text{H}^+) (10^{-10})$	3	2	34	2	1	18
Gradient (km/s/pc)	2	1	14	2	1	12
$\beta$	0.02	0.02	13	0.02	0.02	7

<sup>a</sup> $\Delta v_{\text{NT}}$  is the non-thermal part of the line width:  $\Delta v_{\text{NT}}^2 = \Delta v_{\text{obs}}^2 - 8 \ln(2) \times (kT/m_{\text{obs}})$ .

Fig. 1.— Average  $\text{N}_2\text{H}^+(1-0)$  spectra of selected cores, obtained by summing all the spectra inside the half maximum map contour. The spectra are in antenna temperature units. Three starless cores (L1498, L1544, TMC-2) and three cores with stars, indicated by the symbol “\*”, are displayed. This sub-sample show the variation in the  $\text{N}_2\text{H}^+$  profile from quiescent (L1498) to more “turbulent” starless cores (L1544, TMC-2), and from relatively quiescent cores with stars (L1489), to cores with young stellar objects driving powerful outflows (L1228), to cores with complex internal structure (L1215E).

Fig. 2.— Maps of the  $\text{N}_2\text{H}^+(1-0)$  intensity integrated over the seven hyperfine components. The angular scale is the same for each core. The contours and the grey scale mark the 20%, 35%, 50%, 65%, 80%, and 95% of the map peak, reported in Table 1 (see column 7). The thick contour is the half maximum (50%) level, which defines the core size. Small circles are observed positions and the stars indicate the location of the associated infrared source detected by IRAS. The FCRAO half power beam width (HPBW) is shown in the map of Per 4.

Fig. 3.— Correlations between  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  (from BM89) properties at the map peaks for the cores with distance  $D < 200$  pc: (a) column density; (b) integrated intensity; (c) excitation temperature. Best-fit lines are referred to starless cores (black dots). Cores with stars (grey dots) do not show significant correlations between  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  properties (see text).

Fig. 4.— Distribution of core radii mapped in  $\text{N}_2\text{H}^+$  (shaded histogram) and  $\text{NH}_3$  (thin lines), for the entire sample (*top*), cores with stars (*center*), and starless cores (*bottom*). Cores associated with young stellar objects tend to have smaller sizes in  $\text{N}_2\text{H}^+$  than in  $\text{NH}_3$  maps, suggesting higher central densities than starless cores.

Fig. 5.— The “excitation” mass  $M_{\text{ex}}$ , calculated assuming a spherical core with constant density  $n_{\text{ex}}$  (see text), as a function of the virial mass  $M_{\text{vir}}$  for starless cores (empty circles) and cores with stars (filled circles). Cores with  $M_{\text{ex}}/\sigma_{M_{\text{ex}}}$  or  $M_{\text{vir}}/\sigma_{M_{\text{vir}}} < 2$  are not reported in the figure.

Fig. 6.—  $\text{N}_2\text{H}^+(1-0)$  integrated intensity maps of those cores where “local” velocity gradients have been calculated. The grey-scale levels represent the 30%, 50%, 70%, and 90% of the map peak. Small dots mark the position of observed spectra where the determination of  $V_{\text{LSR}}$  from hfs fit has been possible (see Sect. 3.2). The white arrows show the magnitude and the direction of the velocity gradient calculated by applying the least square fitting routine to the grid of positions centered on the corresponding arrow. The black arrow in the bottom of each panel represents the total velocity gradient listed in Table 5 (the magnitude of the white arrows is in units of the total gradient).

Fig. 7.—  $\text{N}_2\text{H}^+(1-0)$  integrated intensity as a function of impact parameter  $b$ . Symbols are different for starless cores (empty circles) and cores associated with stars (filled circles). Thin (dashed) curves are Model 1 (Model 2) best-fit profiles (see text). Dotted profiles have been obtained by using the normalized integrated intensity of the “thin” hyperfine component ( $F_1, F = 1, 0 \rightarrow 1, 1$ ). Most of the starless cores present a “shallow” structure at  $b < \sim 0.03$  pc, in agreement with results from dust continuum emission maps.

Fig. 8.— Maps of line width (grey scale) overlapped with integrated intensity maps (contours; levels are 30, 50, 70, and 90% of the peak). Grey contours range from  $\Delta v_{\min}$  to  $\leq \Delta v_{\max}$  in steps of  $2 < \sigma_{\Delta v} >$ , where  $< \sigma_{\Delta v} >$  is the mean line width error in the selected positions. Grey areas enclose all the points with  $\Delta v$  values between two adjacent grey contours. The dots mark the positions which have been used in the  $\Delta v$  maps (i.e. where  $\Delta v / \sigma_{\Delta v} \geq 3$  and  $I / \sigma_I \geq 5$ ). Values of  $\Delta v_{\min}$ ,  $\Delta v_{\max}$ , and  $2 < \sigma_{\Delta v} >$  (in  $\text{km s}^{-1}$ ) in each core are the following: i) 0.15, 0.29, 0.05 in L1498; ii) 0.21, 0.53, 0.11 in TMC-2; iii) 0.13, 0.24, 0.05 in L1512; iv) 0.19, 0.39, 0.07 in L1544; v) 0.18, 0.38, 0.08 in L183; vi) 0.24, 0.70, 0.08 in L43; vii) 0.24, 0.85, 0.11 in L483; viii) 0.32, 1.28, 0.21 in L1228; ix) 0.37, 1.91, 0.27 in L1251E.

Fig. 9.— Intrinsic  $\text{N}_2\text{H}^+(1-0)$  line width  $\Delta v$  as a function of impact parameter  $b$  for selected cores with positive (L1498, L1495), null (TMC-2, L1228), and negative (TMC-1C2, B5) correlations (see text for details). Cores with stars are marked with filled symbols whereas starless cores have empty symbols.

Fig. 10.— The variance of the average nonthermal line width of a core as a function of  $< \Delta v_{\text{NT}} >$ . Empty circles represent starless cores, whereas filled circles are cores with stars. Lines indicate how dispersion is expected to increase with  $< \Delta v_{\text{NT}} >$  in a simple model of “cells” along the line of sight (see text). The number of cells is indicated. In both classes of cores, dispersion is increasing with increasing  $< \Delta v_{\text{NT}} >$ , following models with  $N \sim 10$ .

Fig. 11.— Dispersion of the average gradient fit residual (Tab. 5) in a core vs. the average nonthermal line width (Tab. 7). The “cell” model is indicated by thin lines for number of cells equal to 1, 3, 10, and 30, as in Fig. 10. A linear least square fit to the data gives  $N = 13$ . These positive correlations strongly suggest the presence of turbulent motions which cause line width broadening and contribute to line width and LSR velocity dispersion across the cores.











































